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REPORT BY THE COMMITTEE ON MOTOR VEHICLE
EMISSIONS

NATIONAL ACADEMY OF SCIENCES

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

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REPORT BY THE COMMITTEE ON

Motor Vehicle Emissions

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Abstract

An evaluation was made of the technological feasibility, cost and fuel use associated with meeting various light-duty motor vehicle emissions standards for nitrogen oxides, hydrocarbons, and carbon monoxide. Emissions control of conventional automobile engines and alternative engines for automobiles are considered. Costs of emissions control, manufacturing constraints, and field performance and maintenance are analyzed. Various automotive fuels for automobiles and test methods and procedures for emissions and fuel economy are also considered.

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Report by the
COMMITTEE ON MOTOR VEHICLE EMISSIONS

Commission on Sociotechnical Systems
National Research Council

National Academy of Sciences
Washington, DC

November 1974

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The members of the committee selected to undertake this project and prepare this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. Responsibility for the detailed aspects of this report rests with that committee.

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COMMISSION ON SOCIOTECHNICAL SYSTEMS

2101 Constitution Avenue Washington, D. C. 20418

November 22, 1974

Dr. Philip Handler, President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear President Handler:

I am transmitting herewith for your submission by the Academy to the Congress and to the Environmental Protection Agency the Report of the Committee on Motor Vehicle Emissions dated November 1974.

Section I contains the Committee's major conclusions in three pages while Section II is a summary of all the conclusions.

Inevitably, there are topics we might like to have covered which fell outside our work scope as described in the Preface. The Committee hopes, however, that this report will be helpful to the Congress and the Environmental Protection Agency in their respective legislative and administrative roles.

Sincerely,



J. Ross Macdonald, Chairman
Committee on Motor Vehicle Emissions

NATIONAL ACADEMY OF SCIENCES

OFFICE OF THE PRESIDENT
2101 CONSTITUTION AVENUE
WASHINGTON, D. C. 20418

November 27, 1974

The President of the Senate
The Speaker of the House of Representatives
The Administrator of the Environmental
Protection Agency

Sirs:

I have the honor to transmit a report prepared by our Committee on Motor Vehicle Emissions, a committee created by the National Academy of Sciences in 1971 in response to a request by the Administrator of the Environmental Protection Agency for a study of the feasibility of achieving the emissions standards established by statute for light-duty motor vehicles, as directed by the Congress in Section 6 of Public Law 91-604, the Clean Air Amendments of 1970.

This report is the fifth in a series. The previous reports were issued in January 1972, April 1972, July 1972, and February 1973; of these, the February 1973 report was the most significant. In the latter, we expressed serious reservations, based on the state of technology at that time, regarding the ability of catalytic systems for emissions control to provide the desired reductions in light-duty motor vehicle emissions with sufficient reliability and at a reasonable cost. We also called special attention to the recent development, by a Japanese manufacturer, of a 'carbureted stratified-charge' engine which looked very promising for vehicle emissions control.

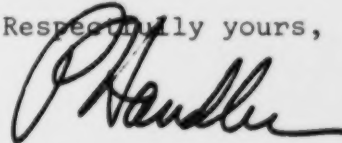
Since the issuance of that report, the latter system has undergone intensive investigation and further development by automobile companies all over the world and continues to be a very promising emissions-control technology. We are especially pleased that significant advances have made catalytic emissions-control systems much more satisfactory for the control of automotive emissions than we anticipated in 1973. The present report reveals that our committee

is confident that present technology suffices for attainment of the 1975 standards and that the 1977 standards will be achieved, albeit there is less certainty with respect to the 1978 standards. Particularly gratifying is the indication by the Committee that implementation of the 1975 and 1977 standards can be effected with little fuel penalty as compared with 1970 engines. Those engaged in the effort to reduce the emission of air pollutants by automobiles may well be proud of these technological achievements.

However, it is also the burden of the scientist to caution regarding the limits of technical capability and technical knowledge. Attainment of the 1978 standards, according to the committee, remains difficult and expensive; the problem of monitoring and maintenance remains unresolved although this requirement now seems somewhat less acute than we had thought; and the present law compels adherence to emissions standards only for the first half of the life of the average automobile. Much remains to be understood about the behavior of air pollutants in the atmosphere and the direct and synergistic effects of these air pollutants on humans, animals, and plant life. There is need to consider the implications of the significant volume of hydrocarbons emitted by evaporation from automobiles and to understand the implications for national policy of the relative contributions of hydrocarbons and of oxides of nitrogen emissions from mobile and stationary sources. There remains a pressing need to gather a more complete perspective of the air pollution problem and to evaluate the relative merits of the various methods available to deal with it.

It is our hope that this report will contribute to the continuing evolution and refinement of the nation's program for cleaner air.

Respectfully yours,

A handwritten signature in dark ink, appearing to read "Philip Handler", written in a cursive style.

Philip Handler
President

PREFACE

The National Academy of Sciences, through its Committee on Motor Vehicle Emissions (CMVE), undertook this study of automobile emissions-control technologies at the request of the Environmental Protection Agency (EPA) pursuant to the mandate of Section 202(c) of the Clean Air Act which directed the EPA to undertake to enter into a contract with the National Academy of Sciences to conduct a comprehensive study and investigation of the technological feasibility of meeting the statutory light-duty motor vehicle emissions standards prescribed in that Act. The first phase of this study began in June 1971. Two semiannual reports and an interim report were issued in 1972, and a final report and seven panel reports were issued in 1973. The current phase of the CMVE study began in October 1973.

The scope of the present study is defined under the contract between the Academy and EPA to be an evaluation of the technological feasibility, cost and fuel use associated with meeting various light-duty motor vehicle emissions standards for nitrogen oxides (NO_x) including the 0.4 g/mi statutory standard. The effect of changes from the legislated standards of 0.41 g/mi for hydrocarbons (HC) and 3.4 g/mi for carbon monoxide (CO) were to be considered to the extent that such changes would influence the choice of technologies for meeting various NO_x standards.

Following the initiation of the current phase of this study, the Energy Supply and Environmental Coordination Act of 1974 was passed by Congress and became Public Law 93-319 on June 22, 1974. This law delays the Interim 1976 Emissions Standards previously established for light-duty motor vehicles for HC/CO/ NO_x of 0.41/3.4/2.0 g/mi until the 1977 model year and delays the statutory standards of 0.41/3.4/0.4 g/mi until the 1978 model year. The law provides for suspension hearings on the HC and CO standards for the 1977 model year to be initiated any time after January 1, 1975. The ability to meet these standards thus became an additional factor to be considered in the preparation of this report.

The contract with the Environmental Protection Agency limits the current study to combustion emissions from light-duty motor vehicles and to the technological methods for controlling them. Thus, emissions from trucks, buses and motorcycles have not been studied nor are various stationary sources treated.

This study also does not include the relationship between automobile emissions and air quality nor does it consider alternative strategies for reducing emissions in polluted areas such as greater use of public transportation or restriction of vehicle use at various times of day or in certain locations. Health effects of air pollution are also not covered. All of the topics of this last paragraph are, however, treated to some extent in the four-volume report by the Coordinating Committee on Air Quality Studies of the National Academy of Sciences--National Academy of Engineering, submitted on September 6, 1974, to the Senate Committee on Public Works.

For the purpose of carrying out the study dealt with in this report, a 16-man committee was established in October 1973. The current members of the Committee are listed in Appendix A. Panels of consultants and a staff were established to collect and analyze data for use by the Committee in formulating its report and conclusions. These consultants and staff members are listed in Appendix B.

Much of the work of the consultants is summarized in the following "Consultant Reports to the Committee on Motor Vehicle Emissions" which are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402:

An Evaluation of Catalytic Converters for Control of Automobile Exhaust Pollutants

Emissions and Fuel-Economy Test Methods and Procedures

Emissions Control of Engine Systems

Field Performance of Emissions-Controlled Automobiles

Manufacturability and Costs of Proposed Low-Emissions Automotive
Engine Systems

These consultant reports and this Report by the Committee on Motor Vehicle Emissions contain information obtained from a variety of sources in addition to the published literature. A request for information was mailed to 628 organizations and individuals and was published in the Federal Register of March 25, 1974, p. 11134. All responses to this request were reviewed by the staff and consultants. In addition, the CMVE staff, consultants, or members of the Committee solicited information directly from the 115 organizations listed in Appendix C.

ACKNOWLEDGMENTS

The Committee on Motor Vehicle Emissions wishes to thank its Executive Director, Dr. Emerson W. Pugh, for his most capable management of the study, and Professor Robert F. Sawyer for his outstanding technical leadership of the Consultant Panels on Technology. These two individuals together with Drs. Nicholas Cernansky, Merrill Ebner, Earl Evans, Richard Matula, and Henry Newhall are especially thanked for providing working drafts of this report for review by the Committee. The technical leadership provided by the consultant panel chairmen in selected areas of the study is acknowledged as is the important contribution of all the consultants (listed in Appendix B) in collecting and evaluating data.

Gratitude is also expressed to the many organizations (listed in Appendix C) who supplied information through direct discussions and formal submissions, and to the numerous other individuals and organizations who volunteered information to aid this study. The cooperation of the Environmental Protection Agency in making certification data and other information available in a timely manner was particularly helpful.

Finally, the Committee on Motor Vehicle Emissions wishes to acknowledge the members of its staff who are listed in Appendix B. The outstanding efforts of these individuals were essential to the successful completion of the study and the preparation of this report.

CONTENTS

I. Major Conclusions	1
II. Summary of All Conclusions	4
A. Schedule for Emissions-Control Technologies	4
B. Feasibility of Meeting Standards in Certification	6
C. Special Aspects of Large-Scale Use of Oxidation Catalysts	11
D. Cost of Emissions Control	11
E. Field Performance and Maintenance	13
F. Automotive Fuels	15
G. Test Methods and Procedures for Emissions and Fuel Economy	16
III. Introduction to Emissions-Control Technology	20
A. Engine Design Considerations	20
B. Emissions	21
C. Combustion Engines	24
D. Control Approaches	31
E. System Characteristics	34
F. Engine Types Considered	35
IV. Emissions-Controlled Conventional Automobile Engines	39
A. Certification and Fleet Data	39
B. Mixture Control	45
C. Combustion Modification	53
D. Exhaust Treatment	55
V. Alternative Automobile Engines for the Near- and Long-Term	64
A. Stratified-Charge Engines	64
B. Diesel Engines	70
C. Rotary Engines	74
D. Long-Term Alternative Engines	77

VI.	Costs of Emissions Control	82
A.	Emissions-Control Hardware Costs	82
B.	Single-Car Cost Analyses	86
C.	The Consumers' View of Costs	95
D.	Impact of New Technology	97
E.	Impact of Delaying or Modifying Standards	99
F.	A Two-Standard Strategy	102
G.	Cost Savings of Smaller Cars	103
VII.	Development, Tooling and Manufacturing Constraints for U.S. Production	106
A.	Development Times	106
B.	Tooling Lead Times	106
C.	Constraints on Rapid Conversion to Alternative Technologies	109
D.	Technology Conversion Studies	112
VIII.	Field Performance and Maintenance	118
A.	Performance in Use	118
B.	Fleet Test Data on Catalytic Converter Systems	122
C.	Performance and Maintenance of Emissions-Control Systems	127
D.	Effect of Emissions-Control Failure on Average Emissions	129
E.	Inspection and Maintenance Programs	132
IX.	Automotive Fuels	135
A.	Unleaded Gasoline	135
B.	Alcohol Fuels	138
C.	Hydrogen	141
D.	Other Gaseous Fuels	142
E.	Water-Fuel Mixtures and Emulsions	142
F.	Sulfur Emissions and Fuel Sulfur	143

X. Test Methods and Procedures for Emissions and Fuel Economy	145
A. Introduction	145
B. Certification Procedures, CVS-CH Test	146
C. Exhaust Emissions	149
D. Evaporative HC Emissions	164
E. Fuel Economy	164
REFERENCES	171
APPENDIXES	180
A. Members of the Committee on Motor Vehicle Emissions	180
B. Staff and Consultants of CMVE	181
C. Organizations Contacted by Members of the Staff, Consultants, or Committee	183
GLOSSARY	187

I. MAJOR CONCLUSIONS*

1. The Clean Air Amendments of 1970 have been followed by major changes in automobile engines and emissions-control systems. Examples of new features in 1975 models are: lean combustion systems; electronic ignition, improved cold-start systems, better carburetion, improved exhaust gas recirculation; and oxidation catalysts (II.B-20).
2. Most 1975 models will meet the Federal 1975 Emissions Standard of $\text{HC/CO/NO}_x = 1.5/15/3.1$ g/mi with about the same fuel economy as 1970 vehicles of equivalent weight and performance, whereas the California Emissions Standard of $0.9/9.0/2.0$ g/mi will be met with about a 5% poorer fuel economy. These represent substantial fuel economy improvements over 1973-1974 vehicles, which had an average 6% penalty for compacts and 15% for standard-to-luxury cars as compared to equivalent 1970 vehicles (II.B-20).
3. The 1977 Federal Emissions Standard of 0.41 g/mi HC, 3.4 g/mi CO and 2.0 g/mi NO_x can be achieved in certification with present technology through improved oxidation catalysts and quick warm-up techniques at an average increased lifetime cost per car over 1970 vehicles of about \$400 (II.B-14, D-1). In spite of inadequate maintenance, vehicles on average are expected to meet the NO_x standard at 50,000 miles of actual use and to meet the HC and CO standards or exceed them by less than 50% (II.E-2).
4. The Federal 1978 Emissions Standard of 0.41 g/mi HC, 3.4 g/mi CO and 0.4 g/mi NO_x can probably be achieved in EPA certification procedures on the existing schedule using catalyst technologies. Since

*All references in this section are to the numbered conclusions in Section II.

no catalyst system has yet achieved 50,000-mile durability and only a few have achieved more than 10,000 miles under laboratory conditions, there is considerable chance that one or more catalyst changes will be required in 50,000 miles as part of the manufacturer's specified maintenance (II.B-1). A typical cost to the customer per change could be as low as \$50 if only the active material is replaced but might be as much as \$300 with some of the systems currently under study. If one assumes, as we have, that a concerted, development effort will result in sufficient improvement in catalyst-system durability to make catalyst changes unnecessary, then an average increase in vehicle lifetime cost of about \$600 over 1970 vehicles is expected, including a fuel-economy penalty of up to 10%, depending on the technologies actually used (II.D-1).

5. The failure of users to perform specified maintenance or to make repairs to emissions-control equipment will increase the percentage of cars, certified for the 1978 Federal Standards, which exceed the 0.4 g/mi NO_x emission level in use. Thus, the average fleet emissions for NO_x at 50,000 miles may be higher than the standard. If the durability of reduction or three-way catalysts is not improved so as to make replacement before 50,000 miles unnecessary and if the specified replacement is not made mandatory, then the amount by which standards will be exceeded on average will be larger (II.E-1).
6. Several alternative approaches for meeting the Federal 1977-1978 Emissions Standards for HC and CO of 0.41 g/mi and 3.4 g/mi, respectively, as well as standards for NO_x at least as low as 1.5 g/mi are being developed in this country: the prechamber, dual-carburetor, stratified-charge (CVCC) engine with thermal reactor now in production in Japan; the lean-burn systems with thermal reactors; the diesel engine now in production in Europe; and the direct fuel-injection, stratified-charge (CCS) engines with oxidizing catalyst

being developed primarily in this country (II.B-16, 17, 18, 19). These systems, especially the last two, which meet the above emissions levels, should provide improved fuel economy over 1970 or 1975 vehicles (II.B-9). The 0.4 g/mi NO_x level mandated by the Federal 1978 Emissions Standard is expected to inhibit the development of these technologies.

7. Reduction of tail-pipe emissions for hydrocarbons below the federal 1975 level of 1.5 g/mi will not have a proportional effect on total vehicular emissions unless evaporative hydrocarbon emissions from vehicles are correspondingly reduced below the present level of about 2.0 g/mi equivalent (II.G-6). As noted in a companion report (A Report by the Coordinating Committee on Air Quality Studies, Vol. 3, September 1974, p. 29), stationary source emissions of hydrocarbons and oxides of nitrogen are as large as mobile source emissions in many urban regions and may need also to be reduced in order to meet ambient air quality standards.
8. Increasingly strict emissions controls have substantially reduced the contribution to air pollution by vehicles in their first 50,000 miles of use. By 1980, cars manufactured in 1975 will, on average, have gone 50,000 miles or more, and, therefore, will not be regulated under current Federal law. Older vehicles are now, and will thus continue to be, a major source of automobile pollution (II.E-8).

II. SUMMARY OF ALL CONCLUSIONS*

There are a number of promising engine technologies for meeting the more stringent emissions-control requirements legislated for 1977 and 1978 or hypothesized by us for the purposes of this study. The schedule for these technologies is discussed in Section A below, while the feasibility of meeting various emissions standards is treated in Section B for those technologies whose results could be mass-produced domestically by 1980.

A. Schedule for Emissions-Control Technologies

1. One technology for meeting more stringent emissions standards with good fuel economy and short lead time is the three-way catalyst with oxygen sensor and electronic feedback. Special carburetors or fuel-injection systems designed for feedback control are required. Limited production facilities for carburetors adaptable to this use are being built in this country now; but not for fuel injection, for which extensive production facilities exist only abroad (VII-D).

2. Dual-catalyst systems are also promising and appear to present no unusual production problems. Production facilities for reduction catalysts would have to be started before January 1976 in order to use them on 1978 models (VII-B).

3. The promising prechamber, dual-carburetor, stratified-charge engine (CVCC) is in production abroad and under development in this country. Whereas modifications to the cylinder head, carburetor, camshaft, etc., are required relative to present engines, much of the present engine tooling can be used. Some engines could be produced domestically as early as model year 1977. With a major effort, we estimate that up to 30% of domestic production could be converted to this technology by 1980 (VII-D).

* All references are to sections in this report.

4. The incentive for U.S. production of rotary engines lies in their small size-to-power ratio and performance characteristics, and not in unique emissions characteristics. Control technologies similar to those projected for the conventional reciprocating internal-combustion engine could be used (V-C1). Therefore, no further special treatment of rotary engines is given in this section. Rotary engines are being produced abroad; however, domestic production of rotary engines previously scheduled by General Motors for the 1975 model year appears to be postponed indefinitely.

5. Domestically produced, diesel-powered cars could be available two and one-half to three years after a decision is made by designing transfer lines to produce engines that are now in production abroad. To outfit all vehicle classes, a wider variety of engine designs would be required, and these could be introduced within five years after a decision is made (VII-B).

6. Designs exist for fuel-injection, stratified-charge engines (CCS). These could be in limited mass production by about 1979 (VII-B).

7. Several more years of development would be required, without assurance of success, before economic gas turbine engines suitable for automobiles are available (V-D1).

8. Stirling- and Rankine-cycle engines show promise for low emissions, but much work is required to develop an economic and durable engine. No mass production should be expected until after 1985 (V-D2, D3).

9. Electric and electric-hybrid vehicles are promising for purposes where distances are short and speeds are low. They are not expected to be in significant use as general-purpose, light-duty motor vehicles in the foreseeable future (V-D4, D5).

B. Feasibility of Meeting Standards in Certification

All observations in this section relate to the legislated or hypothesized emissions standards listed below and deal only with the feasibility of passing the present form of certification test. Additional problems in use are discussed under part E of this section. The engine systems referred to in these conclusions are described in Sections III, IV and V. Their estimated fuel economies and costs are summarized in Tables VI-4 and VI-5 and their earliest possible production schedules are summarized in Table VII-1.

Emissions Standards	Levels for HC/CO/NO _x
Federal 1978	0.41/3.4/0.4 g/mi
Hypothetical 1978	0.41/3.4/1.0 g/mi
Hypothetical 1977	0.9/9.0/1.0 g/mi
Federal 1977	0.41/3.4/2.0 g/mi
California 1975	0.9/9.0/2.0 g/mi
Federal 1975	1.5/15/3.1 g/mi

Federal 1978 Standard for HC/CO/NO_x of 0.41/3.4/0.4 g/mi

1. A number of light-duty motor vehicles equipped with three-way catalysts, electronic sensors and feedback circuitry have been shown to meet these standards at low mileage. A 2% to 3% fuel economy penalty may result over 1970 vehicles if EGR or spark retard is required to help meet the low NO_x standard. Durability results on one car (IV-D5) indicate 20,000 miles can be achieved without catalyst or sensor replacement; however, no catalyst system has met this standard for 50,000 miles and only a few have thus far exceeded 10,000 miles.

2. Certain dual-catalyst systems--e.g., a base-metal, reduction catalyst (Cr, Ni and Cu) preceded by an oxygen getter and followed by an oxidizing catalyst--show promise of performing almost as well as the three-way catalyst system (VI-D4). A lower initial cost but somewhat poorer fuel economy of perhaps 5% to 10% is expected, as shown in Table VI-4.

3. The prechamber, dual-carburetor, stratified-charge engine (CVCC) is expected to be able to meet the standards at least for small cars. Use of EGR to meet this NO_x standard incurs a fuel economy penalty over 1970 vehicles of approximately 15% for subcompacts and more than 25% for large cars--if it is possible at all for large cars (V-A1).

4. Diesel engines are not expected to be able to achieve this standard (V-B). Direct-fuel-injection, stratified-charge engines (CCS) may be able to achieve this standard with a 10% to 20% fuel economy penalty over an uncontrolled CCS, or approximately the fuel use of a typical 1970 vehicle (V-A3).

5. Vehicles powered by gas turbines, Rankine- or Stirling-cycle engines show promise of meeting these standards with few, if any, emissions-control devices. The cost-competitiveness of these systems has not been demonstrated and much development work is needed (V-D).

Hypothesized Standard for HC/CO/ NO_x of 0.41/3.4/1.0 g/mi for 1978

6. Light-duty motor vehicles equipped with three-way catalysts and electronic sensors and feedback systems can meet these standards. Fuel economy equivalent to or slightly better than that of 1970 vehicles is expected (IV-D5).

7. Certain dual-catalyst systems show promise of doing almost as well as the three-way catalyst system with lower initial cost but an expected poorer fuel economy of perhaps 5% (IV-D4).

8. The prechamber, dual-carburetor, stratified-charge (CVCC) engine has been shown to meet the standards in 50,000-mile durability tests for small cars (V-A1). It could probably be certified with EGR for larger cars as well. Little fuel economy loss is expected for small

cars compared to uncontrolled 1970 vehicles; however, as much as a 10% to 15% penalty may result for large cars.

9. Both the diesel with EGR and the direct-fuel-injection, stratified-charge (CCS) engine with EGR and oxidation catalyst are expected to be able to meet this standard. Their fuel economy in miles per gallon is expected to be 10% to 20% better in small cars and 5% to 10% better in large cars than the typical 1970 vehicles for vehicles of equivalent performance (V-B, A3).

Hypothesized Standard for HC/CO/NO_x of 0.9/9.0/1.0 g/mi for 1977

10. This standard can be met by cars equipped with conventional gasoline engines, oxidizing catalysts, extensive use of proportional EGR and air pumps. Fuel economy about 20% poorer than 1970 model cars should be expected. Improved mixture control through advanced carburetor and manifold systems now under development (IV-B1) may permit this standard to be met with limited use of EGR and about 5% loss in fuel economy over 1970 vehicles. These improved mixture-control systems could not, however, be generally available for the 1977 model year.

11. Light-duty motor vehicles equipped with three-way catalysts, electronic sensors and feedback circuits or equipped with dual-catalyst systems will meet this standard. Fuel economy as good as or better than that of 1970 vehicles is expected (IV-D5).

12. The prechamber, dual-carburetor, stratified-charge (CVCC) engine with EGR will meet this standard, with fuel economy similar to 1970 model cars (V-A1).

13. Both the diesel with EGR and the direct-fuel-injection, stratified-charge (CCS) engine with EGR and an oxidizing catalyst are

expected to meet this standard. Their fuel economy in miles per gallon is expected to be 10% to 20% better in small cars and 5% to 10% better in large cars than in typical 1970 vehicles (V-A, B).

Federal 1977 Standards for HC/CO/NO_x of 0.41/3.4/2.0 g/mi

14. This standard can be met by cars equipped with conventional gasoline engines, improved oxidizing catalysts, proportional EGR, air pumps, and somewhat more sophisticated cold-start procedures than now on California 1975 model cars. The fuel economy would be the same or better than for equivalent 1970 model cars (IV-A3).

15. Light-duty motor vehicles equipped with three-way catalysts or dual-catalyst systems will meet this standard, with fuel economy as good or better than 1970 vehicles (IV-D5).

16. The prechamber, dual-carburetor, stratified-charge (CVCC) engine will meet this standard with little, if any, fuel economy penalty over 1970 vehicles (V-A1).

17. The diesel without emissions-control modifications and the direct-fuel-injection, stratified-charge (CCS) engine with oxidation catalyst will meet this standard. Fuel economies should be about 25% better for the diesel and 15% to 20% better for the fuel-injection, stratified-charge engine when compared to typical 1970 vehicles of equivalent weight and performance (V-B, A3).

18. Lean-burn engines using improved air/fuel mixture preparation will probably be able to achieve this standard with little, if any, fuel penalty in comparison to 1970 vehicles (IV-B1).

19. Systems, such as the lean-burn engine with thermal reactor, CVCC with thermal reactor, and diesel, are available which can probably

meet levels of 0.41/3.4/1.5 and possibly somewhat lower NO_x without use of a catalyst and are expected to have no difficulties in meeting this standard in use. Such systems would not require fuel of low lead or low phosphorus content. Fuel economy would be improved over that of a comparable 1970 vehicle (Tables IV-5, V-1, 4).

Federal 1975 Standards for HC/CO/NO_x of 1.5/15/3.1 g/mi

California 1975 Standards for HC/CO/NO_x of 0.9/9.0/2.0 g/mi

20. All domestic cars certified for the California 1975 Standards and about 80% of those meeting the Federal standards will use oxidation catalysts. Almost all cars will use improved EGR, electronic ignition and quick-warm-up techniques. Approximately 90% of California cars will also use air pumps, while only one third of the 49-state cars will have them. Fuel economy of catalyst-equipped cars meeting the Federal standards will be about the same as that of 1970 vehicles of the same weight while those meeting California standards will be about 5% poorer. These represent substantial fuel economy improvements over 1973-74 vehicles, which had an average 6% penalty for compacts and 15% for standard-to-luxury cars as compared to 1970 vehicles. Fuel economy of noncatalyst cars meeting the Federal standards will be slightly poorer for small cars and up to 20% worse for large cars than comparable 1970 vehicles (IV-A).

21. Vehicles having improved mixture preparation through the use of advanced carburetors, together with improved intake and exhaust manifolds, can probably meet the 0.9/9.0/2.0 g/mi standards with fuel economies similar to those of 1970 cars. The absence of an oxidation catalyst should result in a lower first cost than for cars equipped with catalysts. These carburetors might be available for production by the 1978 model year (IV-B1).

C. Special Aspects of Large-Scale Use of Oxidation Catalysts

1. Catalysts will diminish appreciably the emissions of polynuclear aromatics such as the carcinogen, benzo(a)pyrene, as well as the highly odoriferous and reactive aldehydes and mercaptans (IV-D3).

2. The use of lead-free fuel, without catalysts, results in a tenfold reduction in total particulate emissions. The oxidation catalyst will produce a small increase in particulate emissions (compared with the lead-free case), mainly due to sulfuric acid and sulfates (IV-D3).

3. Increased emissions of SO_3 and catalyst debris (possibly containing precious metals) will occur, of which only SO_3 may pose a known health problem (IV-D3).

4. A doubling of the demand for precious metals (such as platinum and palladium, both imported from abroad) has increased our already significant dependence on foreign supplies. The use of these materials is expected to increase for more stringent standards (IV-D3).

5. Possible increases in demand for nickel and chromium to construct heat-resistant, metal-alloy containers may add to the problems of foreign supply. However, the use of Cr and Ni in these containers is not expected to exceed 1% of the total U.S. consumption for any of the proposed systems. The use of base-metal catalysts for NO_x control in dual-catalyst systems could increase the consumption of scarce nickel by as much as 10% (IV-D3).

D. Cost of Emissions Control

1. The estimated average (10 year) lifetime cost per car in 1978 (based on a six-cylinder intermediate) over equivalent 1970 vehicles, of meeting various HC/CO/ NO_x emissions standards with catalyst-equipped

vehicles (stated in 1974 dollars) is as follows (VI-B):

1.5/15/3.1 g/mi	\$250 ± 100
0.9/9.0/2.0 g/mi	\$350 ± 150
0.4/3.4/2.0 g/mi	\$400 ± 200
0.9/9.0/1.0 g/mi	\$400 ± 200
0.4/3.4/1.0 g/mi	\$450 ± 250
0.4/3.4/0.4 g/mi	\$600 ± 350

The large cost uncertainties for the more stringent standards above are largely due to uncertainties in the rate at which new technology is implemented and refined. For example, the \$600 estimated for the most stringent standard assumes adequate durability will be achieved by 1978 to make a catalyst change before 50,000 miles unnecessary. The estimated cost of such a change is as low as \$50 if only the active material is replaced, but it might be as much as \$300 if a converter replacement is required.

2. The estimated lifetime cost of meeting Federal 1975 Standards with catalyst-equipped cars is \$265 as opposed to the \$557 which is estimated for 1973-74 cars designed to meet less stringent standards (Table VI-4, page 89). Over 90% of the \$557 estimated lifetime cost of 1973-74 vehicles is in maintenance and fuel use as opposed to sticker price (VI-B).

3. Vehicles of equivalent performance, equipped with a diesel or CCS engine (with oxidizing catalyst), are predicted to provide a lifetime vehicle cost saving of \$500 to \$900 over catalyst-equipped conventional engines for all emissions standards listed above, with the exception that the diesel is not expected to meet the 0.4 g/mi NO_x standard (VI-B).

4. If the 0.4 g/mi NO_x standard were delayed by two years, an estimated \$7 billion would be saved out of the projected cost of motor vehicle emissions control of \$72 billion for the 1970-85 time frame. Of this \$7 billion saving, more than \$5 billion results from reduced fuel consumption (VI-E).

5. A two-standard strategy in which one third of the 1978 vehicles were produced to meet legislated 1978 standards and two thirds were produced to meet present Federal 1975 Standards could save approximately \$350 in lifetime cost for each car produced to meet the less-stringent standard, or \$2 to \$3 billion per year (VI-F).

6. Over \$2,500 savings per car in lifetime operating costs is possible by shifting from an intermediate, six-cylinder to a subcompact vehicle. About 8% of this saving can be attributed to lower costs of emissions control (VI-G).

E. Field Performance and Maintenance

1. There is little doubt that manufacturers can produce cars capable of meeting the Federal 1978 Emissions Standards with one or more catalyst changes as part of the specified maintenance, but there is expected to be no apparent benefit in vehicle performance or economy for owners who perform this maintenance. Such cars would therefore probably not meet the certification-level standards in use with voluntary maintenance alone, and the average emissions from these vehicles for NO_x would probably exceed the 0.4 g/mi level (VIII-D).

2. Cars can be manufactured which, if properly maintained, will meet the 1977 emissions standard in actual use for 50,000 miles (IV-A3). It is not yet clear whether the performance of specified maintenance will be necessary for the fleet average emissions to remain below the standards; however, we would not expect HC and CO emissions to exceed the standards by more than 50% at 50,000 miles (VIII-D).

3. During the first 50,000 miles, perhaps 5% to 10% of the catalyst-equipped cars may have catalyst failure resulting from engine misfires, etc. (VIII-B). Assuming a 10% failure rate, the average emissions of 1975 vehicles at 50,000 miles would be 35% below (i.e., better than) the

Federal HC standard and 40% below the CO standard if the deterioration in use is no more severe than that projected by the EPA test procedure.

4. The need for emissions-control systems more durable than those used on 1972-74 cars is evident from the amount the average emissions from cars in use currently exceed the standards (VIII-A). Recent improvements in durability which have been achieved, for example, by the use of electronic ignition systems and unleaded fuel, will tend to decrease the number of cars that exceed the standards, as indicated by field-test data on some 500 cars in service (VIII-B, C).

5. Surveys show that between 11% and 15% of pre-1975 vehicles have had their emissions-control systems deactivated (VIII-A). Inspection programs may be required to prevent more widespread deactivation of emissions-control systems which impose a fuel economy penalty.

6. In spite of an effort toward self-improvement in the last two years, there is still an inadequate number of properly trained service personnel to provide emissions-related maintenance specified by manufacturers (VIII-E).

7. Unless substantially more unleaded gasoline is produced than is required to fuel the 1975 cars, local shortages may result in use of leaded fuel which will cause rapid deterioration of the oxidation catalysts (VIII-B).

8. Cars which have gone 50,000 miles or more constitute over half of the car population and account for about 40% of the annual mileage traveled. These vehicles are not regulated under Federal statutes (X-B). They are and will continue to be a major source of vehicular air pollution.

F. Automotive Fuels

1. The incremental processing cost of raising the average clear-pool (unleaded) octane quality in the U.S. to the 91 RON/83 MON level is less than 1% in energy loss and about 0.5¢ per gallon. The price to the consumer may be up to 2¢ higher due to distribution costs, pricing strategies or government regulation (IX-A3).

2. Since 1970, average engine compression ratios in the U.S. have decreased from about 9.5:1 to 8:1, primarily in order to reduce engine NO_x emissions and to allow for use of emissions-control catalysts that require unleaded fuel. The poorer engine efficiency resulting from this reduced compression ratio increases fuel consumption by about 6%, resulting in an increased lifetime fuel cost to the consumer of about \$200 to \$300. The use of unleaded fuel is expected to save about this much money in reduced maintenance costs (IX-A1).

3. At exhaust-emissions levels required by legislated standards, most lead-tolerant-vehicle systems have poorer fuel economy than the lead-intolerant systems using exhaust catalysts (IX-A1).

4. Alternative power plants that look promising for the future appear to have modest octane requirements or no octane requirement, and, therefore, will not benefit from lead antiknock additives (IX-A2).

5. Methanol can give substantial reduction in NO_x emissions relative to gasoline. However, the practical problems associated with methanol use are numerous; thus, it may not be justified as an alternative to gasoline on an emissions-reduction basis alone (IX-B1).

6. Methanol-gasoline blends present many of the practical problems associated with use of straight methanol, in addition to new problems

associated strictly with blending phenomena. These blends do not appear to reduce exhaust emissions substantially; as a consequence, their use cannot be justified on the basis of emissions considerations alone (IX-B2).

7. Hydrogen can be a very low-emissions fuel; however, due to its relatively low volumetric energy content, hydrogen storage in sufficient quantities for adequate vehicle range does not appear feasible (IX-C).

8. Vehicle systems for partial conversion of gasoline to hydrogen are under study. Low NO_x and CO emissions levels have been encouraging; however, major problems related to overall system thermal efficiency and excessive HC emissions remain to be solved (IX-C).

9. Commercially available systems for use of natural gas or petroleum gas fuels can reduce HC and CO emissions under cold-start conditions. However, these fuels suffer from limited vehicle range. Since most, if not all, of the emissions benefits of these fuels can be equalled with late-model vehicles using conventional gasolines, there does not appear to be an incentive for large-scale conversion to gaseous fuels (IX-D).

10. Water injection into engines can reduce NO_x emissions in the same manner as EGR. By comparison, water induction involves significantly more expense and inconvenience and appears to offer no advantage over EGR. Water-fuel emulsions might reduce NO_x emissions and particulates in diesel engines (IX-E).

G. Test Methods and Procedures for Emissions and Fuel Economy

1. The CVS-CH test cycle is a sufficiently accurate representation of urban driving patterns to be used for purposes of determining light-duty motor vehicle exhaust emissions (X-C1).

2. There are variations in exhaust-emissions measurements among repeated tests. For a typical 1975-76 vehicle in a given cell, or from cell to cell at one laboratory, the standard deviation, expressed as a percent of the mean, can be expected to range between 10% to 25%, 15% to 30% and 5% to 15% for HC, CO and NO_x, respectively (X-C2).

3. To reduce the variability of exhaust-emissions tests, ambient test-cell temperature and humidity should be more carefully controlled than presently required during the CVS-CH test method. In addition, appropriate correction factors relating ambient pressure and all exhaust emissions should be developed and incorporated in the CVS-CH test method (X-C3).

4. Routine mandatory exhaust-emissions-correlation-test programs between testing laboratories should be established, since systematic errors of as much as 20% to 30% have been reported between various test laboratories (X-C2).

5. Statistical variability associated with the determination of deterioration factors may reflect the special circumstances of the test rather than the capability of the underlying technology. Certification-durability factors are usually based on tests of only one vehicle; an averaging over a large group of vehicles would be preferable. Care must be taken, however, to avoid averaging the deterioration factors from dissimilar emissions-control systems, since this would permit undesirable technologies to be certified as a result of being averaged with more desirable technologies (IV-A; X-C5).

6. Evaporative hydrocarbon emissions, based on tests employing the SHED test method, from vehicles equipped with present-technology, evaporative-control systems, have been shown to be equivalent to approximately 1.9 g/mi in Los Angeles and 2.4 g/mi in Denver. These

results were obtained on systems in which evaporative emissions, measured by Federal test procedures, were thought to be 95% controlled with respect to uncontrolled evaporative levels of approximately 3.0 g/mi. In addition, refueling losses are estimated to be approximately 0.4 g/mi. Reduction in emissions from these sources must be achieved before reduction of exhaust HC emissions below the present standard of 1.5 g/mi will have a significant effect on total HC emissions from light-duty motor vehicles. An accurate test method and procedure for measuring evaporative HC emissions must be developed and implemented as soon as possible. Careful evaluation of the situation may show that the SHED test method is adequate for this purpose (X-D).

7. Significant fuel economy penalties are incurred when a light-duty motor vehicle is driven on a short trip that is initiated from a cold-start condition. Since a significant number of urban trips are very short and initiated from a cold start, an urban fuel economy driving cycle should include a cold-start phase. On balance, the CVS-CH driving cycle is a sufficiently accurate representation of urban driving patterns to be used as the urban fuel economy cycle (X-E1).

8. Significant vehicular miles are driven in both urban and non-urban modes, and fuel economy may differ by approximately 50% in these two driving modes. Therefore, to obtain a reasonably accurate determination of the fuel economy of a vehicle, two driving cycles, one designed to represent urban driving and one designed to represent highway driving, are needed to allow a rational consumer choice (X-E1).

9. Either the Carbon Mass Balance method or the direct measurement of the mass or volume of fuel consumed can be used to determine fuel economies associated with the CVS-CH test method. Fuel economy measurements on the CVS-CH test cycle based on the Carbon Mass Balance method tend to be about 3% higher than direct measurements (X-E2).

10. Limited data presently available indicate that fuel economy tests incorporating chassis dynamometers, with suitably fine inertia-weight controls, can be successfully employed to determine fuel economies for urban driving cycles where inertia forces and idle conditions rather than road loads dominate light-duty motor vehicle fuel consumption (X-E2).

III. INTRODUCTION TO EMISSIONS-CONTROL TECHNOLOGY

A. Engine Design Considerations

The current state of automotive emissions control is necessarily a compromise resulting from the superposition of emissions regulations upon an engine that was developed over a period of 60 years with practically no consideration of the composition of the exhaust. The dominant automotive power plant configuration of today is a reciprocating, spark-ignition, carbureted gasoline engine, the basic design of which has remained unchanged since the early adaptation of the Otto cycle engine to the automobile. The development of the current engine has occurred with two primary design objectives:

1. Low cost, and
2. High power-to-weight and power-to-size ratios.

Secondary design objectives were the following:

3. Good durability,
4. Low maintenance and high reliability, and
5. Low fuel consumption.

The resulting engine should be given an outstanding rating on the attainment of at least the first four of these goals. The spark-ignition engine is a high-performance, durable, reliable and low-priced product. Fuel economy is so strongly tied to vehicle weight that focusing upon the engine when seeking improvements in gasoline mileage is dangerous. An increasing concern with fuel economy is, nonetheless, renewing interest in improving engine efficiency and further advancements in this area are to be expected.

During the past 10 years, an additional design objective of

6. Reduction of pollutant emissions

has been added to those which were dominant during the development of the automobile engine. Approaches to the minimization of emissions have consequently been constrained by a desire to disturb as little as

possible the existing engine design. It is neither surprising nor necessarily bad that current emissions controls involve minor engine modifications and adjustments and concentrate upon "add-on" devices, particularly systems to cleanse the exhaust after it has left the engine. Had the consideration of exhaust emissions been important during the development of the automotive engine, however, a design different from the current engine would have been a likely result.

B. Emissions

Automotive emissions come primarily from the engine exhaust and are the result of the combustion of hydrocarbon fuels with air. Another source of emissions is the direct evaporation of gasoline or oil.

1. Exhaust Versus Evaporative Emissions

In an ideal combustion process, only water and carbon dioxide would be produced and neither of these is generally considered to be an air pollutant. In practice, however, a number of other chemical compounds, including those classified as air pollutants, are found in automotive exhaust. Although present in only fractions of a percent or parts per million quantities, these compounds constitute an air pollution problem and their reduction is the focus of current emissions-control efforts.

Automotive evaporative-emissions-control systems introduced in 1970 were thought to be effective in preventing the direct emissions of gasoline fuel vapors into the atmosphere; however, this belief has been challenged by recent measurements. Use of the Sealed Housing for Evaporative Determinations (SHED) Method for measuring evaporative hydrocarbon emissions gives levels approximately 10 times greater than the specified Canister Test Method as discussed more fully in Section X-D.

2. Controlled Pollutants

Three exhaust emissions--hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x)--are currently under statutory control. The oxides of nitrogen measurement gives the sum of nitric oxide (NO), which is the dominant species, and nitrogen dioxide (NO_2). The measurement of CO is specific.

The measurements of hydrocarbons are, however, ambiguous. Ambient hydrocarbon air quality standards exclude methane, presumably because of the very large "natural" emissions of methane from plants, animals, etc. Inconsistently, methane is included in the statutory hydrocarbon emissions levels established for light-duty vehicles on the assumption that measures to control total hydrocarbons (as measured by the Flame Ionization Method) will result in a satisfactory control of all gaseous organic compounds, regardless of specific chemical compositions. Although no evidence exists which refutes this assumption, continued surveillance of the chemical composition of exhaust hydrocarbons appears advisable. Introduction of new control technologies and changes in fuel composition are anticipated to produce changes in exhaust hydrocarbon compositions.

3. Uncontrolled Pollutants

The three controlled pollutants are believed to be the most important automotive emissions and, therefore, have received the greatest attention. Additional pollutants are receiving increased attention as the combined result of a better understanding of the importance of various pollutants to air pollution, the development of new test methods and the actual or possible increase in emissions of unregulated pollutants resulting from new control methods, new propulsion technology, or changing fuel consumption. A partial list of species of possible concern and potential regulation follow:

Particulates: A total mass particulate standard of 0.1 g/mi has been proposed.^{3.1*} The importance of size distribution and chemical composition of particulates is recognized but remains ill-defined. Difficulties in the collection of particulate samples and their analysis for total mass emitted, particle sizes and chemical composition contribute to the uncertainty in assessing the nature of the particulate-emissions problem. The development of valid measurement methods is essential.

Aldehydes: Aldehydes are commonly produced in combustion engines and constitute both primary and secondary air pollutants.^{3.2} Hydrocarbon control methods generally, but not always, are effective for aldehydes as well. Hydrocarbon measurement methods are largely insensitive to aldehydes.

Sulfur compounds: Combustion processes generally convert the sulfur in fuels to SO_2 . Since gasoline contains very little sulfur, the regulation of sulfur compounds from vehicles has not been considered necessary. The observed conversion of SO_2 to SO_3 , a compound with increased air pollution potential, in catalytic exhaust reactors has increased concern for vehicular emissions of sulfur compounds.^{3.2} An increased use of diesel fuel, which contains more sulfur than gasoline, would also increase the importance of vehicular emissions of sulfur compounds.

Carcinogens: Combustion processes are known to produce hydrocarbon compounds that have been identified as carcinogenic, particularly benzo(a)pyrene (BAP).^{3.2} The air pollution potential of these compounds has not been assessed.

Ammonia: Ammonia also is produced in combustion processes. The conversion of nitric oxide to ammonia across reduction catalysts has been observed.^{3.3}

*References are listed at the end of the report (page 171).

Odorants: The identification of the chemical composition of odorants found in combustion-engine exhaust remains incomplete. Aldehydes and mercaptans are known to contribute to exhaust odor.^{3.1}

An assessment of the role of these compounds in air pollution and the importance of vehicular sources is required. Since new emissions-control technologies and new propulsion systems may increase vehicular contributions of these unregulated pollutants, the potential impact on air pollution must be of concern. Vehicular-emissions standards on these pollutants would necessarily have an effect on the development of emissions controls and the introduction of new propulsion systems. Emissions standards on some of these pollutants could discourage or prevent the development and introduction of certain new emissions-control and propulsion technology.

The assessment of the need for the regulation of additional vehicular emissions should proceed rapidly and, if necessary, additional standards should be established. The development and introduction of new emissions controls and engine systems will be adversely affected by uncertainties in possible future regulation of additional emissions.

C. Combustion Engines

In the evaluation of emissions-control technology, the identification of common features and constraints is useful. Motor-vehicle propulsion is dominated by combustion engines and is likely to remain so for the remainder of this century. Most of these engines burn a liquid hydrocarbon fuel with air to produce combustion products at high temperature and pressure. These products are then allowed to expand against or across a reciprocating or rotating surface to produce the useful work which propels the vehicle.

1. Engine Types

Current and proposed combustion engines are categorized according to the nature of the combustion process. Internal-combustion engines utilize the combustion products as the fluid to be expanded to produce work. External-combustion engines employ a second, separate working fluid. Relieving the combustion products from the constraints of also acting as the working fluid generally makes control of the combustion process easier and allows the attainment of very low emissions levels. The external-combustion engines necessarily suffer the complexity of a second fluid and the necessity of heat transfer surfaces to transfer energy from the combustion products to the working fluid.

A second classification describes the time duration of the combustion process. In intermittent-combustion engines, charges of fuel and air are ignited and burned repetitively, at the rate of from about 5 to 50 times per second. In continuous-combustion engines, the fuel and air are continuously supplied to a combustion chamber with no need for repeated ignitions. An advantage of the intermittent-combustion engine is that working fluid temperatures substantially in excess of engine surface temperatures are possible. The temperature of the working fluid in continuous-combustion engines, both of the internal and external types, is usually fixed by material limitations.

The most important engines of these types are summarized in Table III-1. A number of other types of engines, such as the closed-cycle gas turbine, which is an external-combustion Brayton-cycle engine, have been omitted, generally because they are more complex and less efficient than the engines listed. Most of these basic engines can be configured with either a reciprocating or rotating expander so that a large number of combinations of combustor and expander types are at least theoretically possible. Many possibilities exist for combining these engine types to produce compound engines. The turbocharged diesel is an example which combines the Brayton and diesel cycles.

TABLE III-1

Engine Classification by Combustion Characteristics

	INTERNAL COMBUSTION	EXTERNAL COMBUSTION
INTERMITTENT COMBUSTION	OTTO CYCLE (Spark Ignition) Conventional Stratified Charge Rotary DIESEL CYCLE (Compression Ignition)	
CONTINUOUS COMBUSTION	BRAYTON CYCLE (Gas Turbine)	RANKINE CYCLE (Steam Engine) STIRLING CYCLE

NONCOMBUSTION "ENGINES": ELECTRIC, FLYWHEEL

Electric and flywheel propulsion units are two "noncombustion engines." They produce no direct pollutant emissions.

2. Combustion Processes

The combustion process is concerned with the release of the chemical energy contained in the fuel. Even in current engines, this process is extremely efficient with more than 95% of the available chemical energy released in the combustion process. One of the most important parameters affecting the combustion is the air/fuel mixture ratio. If less than the required amount of air is provided, increased concentrations of carbon monoxide and hydrocarbons result. If the air supply becomes excessive, the engine will lose power, begin to misfire and the combustion will be incomplete. Without emissions constraints, most engines operate within the (air/fuel) ratio range of 12:1 to 16:1.

During cold start, choking is required to make the air/fuel ratio extremely rich and, thus, compensate for the low vapor pressure of cold gasoline. Much of the hydrocarbons and carbon monoxide is emitted during the first 2 minutes of the 23-minute certification test cycle. By heating the incoming air and providing hot spots for fuel evaporation, choking times have been reduced to less than one minute, yielding a reduction in HC and CO emissions.

The mixture ratio has a strong influence on the pollutant emissions. Conventional engines show the general characteristics of Figure III-1, with hydrocarbons and carbon monoxide decreasing as the air/fuel ratio is increased. Nitric oxide, which is formed only at high temperatures, is a maximum for air/fuel ratios slightly leaner than stoichiometric. The CO emissions decrease for the lean air/fuel ratios. Hydrocarbon emissions also decrease on the lean side of stoichiometry, but with current engines, they show an upturn as the air/fuel ratio is further increased because the mixture becomes too lean to support complete combustion.

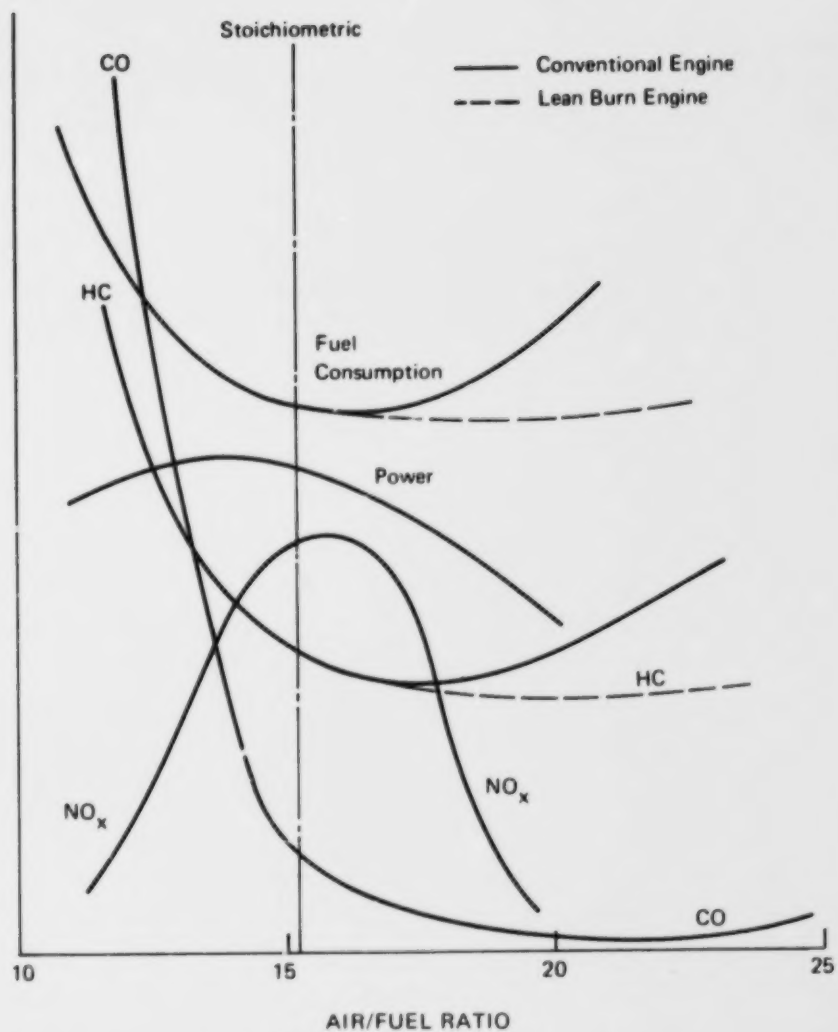


FIGURE III-1 The Relationship of Typical Engine Emissions and Performance to Air/Fuel Ratio. The Vertical Scale is Linear and Shows Relative Rather than Absolute Values for Each Parameter.

Diesel engines and stratified-charge engines are designed to operate with large excesses of air. Combustion in these engines is achieved by stratifying the fuel charge prior to ignition and by allowing the flame to propagate from fuel-rich regions into leaner regions. Conventional spark-ignition engines have been modified to operate at higher air/fuel ratios as well. This has been accomplished by improving the homogeneity of the air/fuel mixture.

By operating very lean, these systems achieve relatively low levels of NO_x emissions without EGR or catalysts and provide good fuel economy. Carbon monoxide emissions are also low. Hydrocarbon emissions tend to rise as high air/fuel ratios are achieved due to misfires in spark-ignited engines. Conventional and stratified-charge engines, therefore, require the use of oxidizing catalysts or thermal reactors to meet present hydrocarbon standards.

3. Engine Efficiency

The fraction of the energy in the high-temperature combustion products which can be converted into useful energy depends upon both the particular engine cycle and the nature of the real losses, such as friction and heat transfer. As a general rule, high temperatures of the working fluid at the beginning of the expansion process and low temperatures at the end of the expansion are desired. It follows that, for good efficiency, high compression or high pressure ratios are favored and, somewhat less obviously, a low-specific-heat working fluid is desirable in most cases. For internal-combustion engines, fuel-lean mixtures give the lowest specific heat ratios. It is always desirable to maximize the ratio of useful work produced to losses sustained through engine friction, engine accessories, cooling water, and the pumping of the incoming air. Actual engine efficiencies vary from 0% (at idle) to about 35% at full power for the best automotive engines (Figure III-2). The relative efficiencies of engines under actual-use conditions involve substantial part-load operation, cold starts and

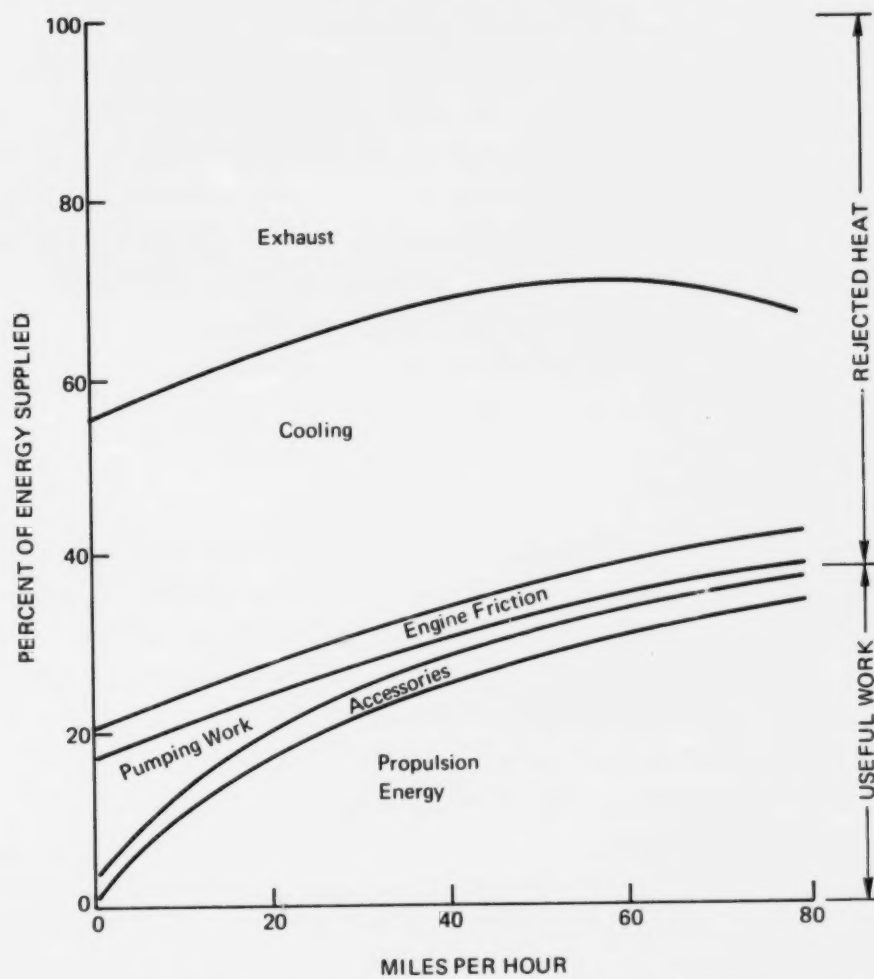


FIGURE III-2 Typical Engine Energy Balance (Approximate).

transient operation, and are probably adequately inferred from vehicle fuel economy data.

The relationships between engine efficiency and emissions are complex and indirect. The reduction of emissions insures neither a reduction nor an increase in engine efficiency, with the citing of examples of both cases possible.

D. Control Approaches

Exhaust emissions-control methods can be divided into three major categories according to whether the approach primarily concerns the mixture before combustion, the combustion process itself, or the products of combustion (Figure III-3). Superficially, it would appear that approaches which occur before or during the combustion process would have some inherent advantage over combustion-product treatment methods in that they prevent pollutant formation rather than attack the problem after the fact. However, since exhaust treatment tends to decouple emissions control from the traditional engine-design constraints, there may be an inherent advantage to this approach, especially in the control of emissions from engines whose design has evolved without emissions constraints. Given the luxury of pursuing an optimally designed engine, one hopefully would seek the best configuration under the simultaneously applied constraints of cost, weight, size, durability, reliability, smoothness, noise, safety, fuel consumption and emissions.

1. Mixture Control

The importance of mixture control has already been suggested by the strong role of the air/fuel ratio in determining engine emissions, fuel economy and power. Additional topics under the subject of mixture control include fuel vaporization, the physical and chemical characteristics of the fuel, distribution of the air/fuel mixture to each cylinder in the engine and the addition of exhaust gases to the incoming mixture (EGR).

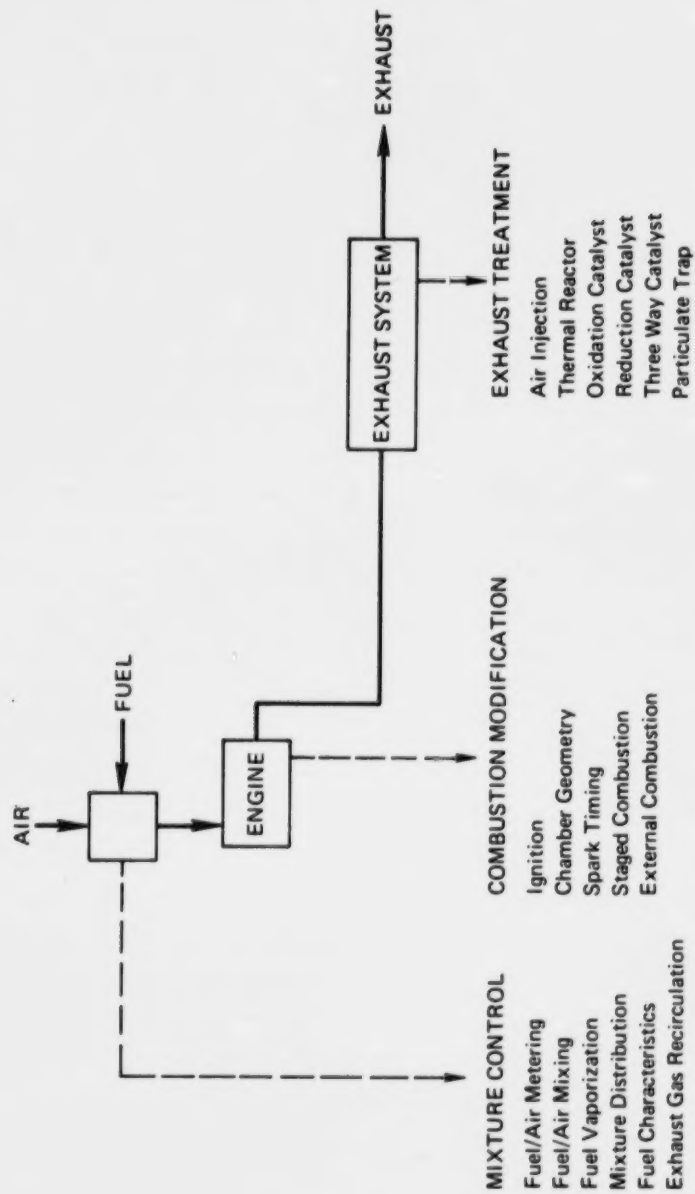


FIGURE III-3 Approaches to the Control of Engine Emissions.

2. Combustion Modification

The objective of modification of the combustion process itself is to improve the combustion so as to reduce emissions or to allow operation of the engine under conditions which minimize pollutants but which ordinarily are not possible. The flexibility of the conventional spark-ignition engine to accept substantial combustion modification is limited, so these approaches generally suggest new or different engines, ranging from the modestly changed, stratified-charge engines to the fundamentally different external-combustion engines.

3. Exhaust Treatment

The first efforts in exhaust treatment have been to promote the oxidation of hydrocarbons and carbon monoxide. In principle, any undesirable exhaust component should be susceptible to removal through an appropriate exhaust-treatment procedure. Compounds that cannot be converted to nonpollutants may be collected for later disposal.

Carbon monoxide and hydrocarbons are eliminated through burning (or oxidation) to carbon dioxide and water. This can be accomplished either homogeneously at high temperatures in a thermal reactor or heterogeneously over a catalyst at much lower temperatures. Achieving the temperatures necessary for the thermal reactors requires "de-tuning" the engine in such a way as to increase the exhaust temperature above the normal 900°-1100°F. The lower temperatures required by the catalytic system effectively "de-couple" the exhaust purification and the engine parameters, a factor that should allow higher performance and more efficient operation of the automobile.

Conversion of NO_x has proceeded along two approaches: the dual-bed system (and sometimes three-bed systems), and the three-way system. In the dual-bed system, the combustion process involves net fuel-rich engine operation with passage of the exhaust gases first over a NO_x reduction catalyst that favors the formation of nitrogen rather than

ammonia. Any ammonia formed in the first catalytic reactor will tend to be oxidized back to NO_x in the oxidation reactor. In the three-way system, a single catalyst is used for conversion of HC, CO and NO_x . This catalytic system requires very close control of the A/F mixture at the stoichiometric ratio. This is difficult, if not impossible, to achieve with conventional carburetors, and, therefore, current development work employs oxygen sensors and electronic feedback to control the carburetor or fuel-injection system.

E. System Characteristics

Emissions controls must be evaluated in terms of their total impact upon the engine and vehicle, not simply in terms of their effectiveness in reducing emissions. Emissions-control systems have been evaluated, wherever possible, in terms of the following six characteristics.

1. Emissions

The emissions are, of course, of primary concern. Unless otherwise noted, the emissions of the regulated hydrocarbons, carbon monoxide and oxides of nitrogen pollutants are reported in grams per mile (g/mi) as measured by the 1975 Environmental Protection Agency Constant Volume Sample, Cold- and Hot-Start procedure (CVS-CH). Unregulated pollutants also are noted if they are deemed to be of potential concern.

2. Fuel Economy

Fuel economy is reported here as measured using the same (CVS-CH) test procedure that is used for emissions certification. Determination of fuel consumption is made by the Carbon Mass Balance Method.

3. Other Performance Parameters

The effect of the emissions-control system upon other performance

parameters, such as power, engine size, engine weight, smoothness, noise, fuel flexibility and safety, are noted when important differences from conventional engines are evident.

4. Manufacturability

The question of manufacturability deals with the availability of capital for the construction of required manufacturing facilities, the ability of the machine-tool industry to build the required tooling, and the availability of natural resources. The manufacturability is reported as the estimated date for the first possible mass production, measured by one transfer line or a minimum of 200,000 units per year, of the item or technology.

5. Reliability and Maintenance

Special problems regarding the inherent reliability of the control system, its effect on the reliability of the engine and the requirements for and availability of maintenance services are noted where appropriate.

6. Potential Improvements

While some systems are highly developed and near their optimum design, others are only in early stages of development. Where a substantial opportunity for improvement of the system is apparent, this potential is noted.

F. Engine Types Considered

Descriptions and evaluations of existing and potential emissions-control systems are grouped according to the basic engine types. Some of the emissions-control systems may, of course, be adaptable to more than one engine type. An introduction to the control system evaluated is provided in the following outline of the engine types considered,

roughly according to the earliest possible date of their initial mass production (Figure III-4).

1. Current Engines

The preponderance of the 1975 model-year cars sold in the United States will be powered by conventional, spark-ignition gasoline engines. These engines are expected to dominate United States automobile sales until at least the mid-1980's.

Honda will market the first cars powered by stratified-charge engines and at least two manufacturers, Mercedes-Benz and Peugeot, now sell diesel-engine cars. Mazda currently sells rotary-engine vehicles in the United States. Total sales of vehicles with these non-conventional engines is estimated to be about 2% of total automobile sales for model year 1975. No United States manufacturer is represented in this group. While these vehicles further demonstrate the technology of the stratified-charge, diesel and rotary-engine vehicles, their total impact in the United States car population remains small. Accordingly, they more properly should be considered as near-term rather than current engine types.

The new emissions-control technology of the exhaust oxidation catalyst will be used on the majority of the conventional-engine 1975 vehicles. An increased use of fuel-injection systems is being made by the foreign manufacturers while United States production engines are almost entirely carbureted. The catalyst-equipped vehicles all use lead-free fuel. Many of the 1975 cars employ an improved exhaust gas recirculation system for NO_x control.

2. Near-Term Engines

Three engine systems which are basically different from the conventional spark-ignition engine are potential candidates for large-scale introduction within a near-term period of five years; that is,

CURRENT	NEAR TERM	LONG TERM
BEFORE 1920	1976-1980	AFTER 1980
○ Conventional Spark Ignition		
	○ Stratified Charge	
	○ Rotary	
	○ Diesel	
		○ Gas Turbine
		○ Electric
		○ Steam
		○ Stirling

FIGURE III-4 Earliest Demonstration of Technological Feasibility for Domestic Mass-Production of Automotive Engine Types.

during the model years 1976-1980. These are the diesel, the rotary and one or more versions of the stratified-charge engine. The technology of all of these engines has been demonstrated and limited mass production of some of these for automotive use has been established by foreign manufacturers. The development of improved versions of all three engine types is in progress. Expansion of production of any one of these is likely to be strongly influenced by considerations of its fuel economy relative to conventional engines and by the emissions standards that it must meet.

3. Long-Term Engines

Any large-scale introduction of gas turbine, steam or Stirling engine vehicles is unlikely during the next five years. Low-performance electric vehicles may be mass-produced during this next five years, but not general-purpose electric vehicles, which could compete with current combustion-engine vehicles. Large-scale use of these engines in automobiles can occur only after 1980.

IV. EMISSIONS-CONTROLLED CONVENTIONAL AUTOMOBILE ENGINES

A. Certification and Fleet Data

1. Certification Data from 1975 Models

As a result of substantial efforts by the automobile industry, the conventional spark-ignition engine has been modified so as to permit numerous light-duty motor vehicle classes to be certified for the Interim 1975 Federal Standard for HC/CO/NO_x of 1.5/15/3.1 g/mi and also the 1975 California Standard of 0.9/9.0/2.0 g/mi. As of September 15, 1974, 46 domestically produced vehicle families, representing 184 individual vehicles, had been certified for the Federal 1975 Emissions Standard and 31 domestically produced vehicle families, representing 109 individual vehicles, had been certified for the California 1975 Standard. In addition, 46 individual vehicles of foreign manufacture had been certified for the Federal Emissions Standard and 59 for the California 1975 Standard.^{4.1}

Because of vehicle-to-vehicle and test-to-test variability, the manufacturers design their vehicles with a substantial safety factor to ensure that they will, in fact, be certified. This safety factor is also encouraged by the future cost of recall if vehicles fail on average to meet the mandated standards when in customer use. A simple average of the emissions, corrected for the deterioration factor, for the vehicle families of each domestic company is given in the first three columns of Table IV-1, and the fraction of the legal emissions level which this represents is shown in the last three columns.

In actual use, it is likely that the average emissions of these vehicles will be higher for two reasons: first, the deterioration of the systems in use will be larger due to poorer maintenance and also due to many more cold starts than in the EPA 50,000-mile durability test, and, second, emissions-system failures in use are likely to go uncorrected, thus permitting the engine emissions of such cars to enter the atmosphere without any treatment. These considerations are discussed more fully in Section VIII.

TABLE IV-1
Average Emissions of 1975 Certification Vehicles
(As Corrected Using the 50,000-Mile Deterioration Factor)

	Emissions in g/mi			Fraction of Standard		
	HC	CO	NO _x	HC	CO	NO _x
Federal 1975						
AMC	0.65	6.7	2.5	0.43	0.45	0.80
Chrysler	0.74	7.7	2.5	0.49	0.51	0.82
Ford	0.81	9.2	2.4	0.54	0.61	0.78
GM	0.83	8.0	2.3	0.55	0.53	0.74
Weighted Average*	0.80	8.2	2.4	0.53	0.55	0.76
California 1975						
AMC	0.42	4.9	1.7	0.47	0.54	0.87
Chrysler	0.48	6.1	1.6	0.53	0.67	0.82
Ford	0.52	5.6	1.3	0.58	0.62	0.67
GM	0.65	5.5	1.6	0.72	0.61	0.82
Weighted Average*	0.58	5.6	1.6	0.64	0.62	0.78

*Weighted average assumes the following market shares: AMC, 3%; Chrysler, 16%; Ford, 27%; and GM, 54%.

Source: This Table is taken from Reference 4.1.

One factor that stands out in the certification data is the variation in deterioration factors from family to family. This is summarized in Table IV-2. This factor and its variability are sufficiently low for vehicles without catalysts that uncertainties in its determination are of little consequence. However, for catalyst-equipped cars, the deterioration factor is substantially larger on average and its variability is large and significant. There appears to be little understanding of the causes of the variability from one system to another so there is some temptation to take one average deterioration factor for all catalyst-equipped vehicles. However, the deterioration is not a function of the catalyst alone. Rather, it is caused by the interaction between the catalyst and the specific engine system. Such an averaging would, therefore, tend to benefit poor system designs at the expense of the better designs.

What is really needed is a better understanding of the engine characteristics that lead to catalyst deterioration. As these are better understood through experience and this information is reflected in better engine-control designs, it should be possible to meet much lower standards easily with catalyst-equipped vehicles.

2. Lower Standards Met by 1975 Certification Vehicles

Of the 109 domestic, light-duty motor vehicles certified for the California 1975 Standards, eight, or 7%, also satisfy the Federal 1977 Emissions Standards as shown in columns one and two of Table IV-3. Considering the large average safety factor the manufacturers are using and the spread in deterioration factors and emissions data, little significance should be attached to the fact that a small number of domestic vehicles designed to meet the California 1975 Standards also meet the Federal 1977 Emissions Standards. What is more significant is that General Motors, which in many respects is the leader in catalyst technology, has been able to tune its cars so that only one of its

TABLE IV-2

Deterioration Factors for 50,000 Miles

Federal 1975 Standards		HC	CO	NO _x
7 families (no catalyst)	low ¹	1.00	1.00	1.00
	average	1.05	1.15	1.04
	high	1.28	1.58	1.24
	std. dev.	10%	19%	9%
39 families (catalyst-equipped)	low	1.00	1.00	1.00
	average	1.68	1.40	1.12
	high	3.67	2.94	1.47
	std. dev.	36%	38%	13%
California 1975 Standards				
20 families (catalyst-equipped)	low	1.03	1.00	1.00
	average	1.61	1.50	1.06
	high	2.84	2.46	1.45
	std. dev.	28%	31%	9%

Source: This analysis is based on the data contained in Item 9 of Reference 4.1

¹When a measured deterioration factor is less than one, it is officially listed as 1.00. This results in a higher average deterioration factor being listed in this Table (which is based on the official printout) than would result if the values less than one had been listed. It also tends to reduce the calculated standard deviation somewhat from what would be obtained from an analysis of the data including deterioration factors less than one.

TABLE IV-3

Total Number of Vehicles Certified for California 1975 Standard
and the Number (and percentage) of These Able to Meet
Certain More Stringent Standards

Manufacturer	Calif. 1975 0.9/9.0/2.0		Federal 1977 0.4/3.4/2.0		Hypothesized 0.4/9.0/2.0		Hypothesized 0.9/3.4/2.0	
	no.	(%)	no.	(%)	no.	(%)	no.	(%)
AMC	16	(100)	1	(6)	6	(38)	3	(19)
Chrysler	21	(100)	2	(9)	7	(33)	0	(0)
Ford	26	(100)	4	(15)	4	(15)	5	(19)
GM	46	(100)	1	(2)	4	(9)	5	(11)
Foreign	62	(100)	21	(34)	38	(61)	28	(45)

Source: Reference 4.1

vehicles meets the Federal 1977 Emissions Standard--and presumably, therefore, more GM cars avoid the small fuel economy penalty that might result from meeting the stricter standard. In contrast, 34% of the gasoline-powered vehicles of foreign manufacture, certified for the California Standard, also meet the Federal 1977 Emissions Standard.

There is a strong indication from these data that many of the catalyst-equipped cars now certified in California could, with recalibration, meet the Federal 1977 Emissions Standard as well.

Further progress in catalyst-system durability, which seems very likely in this new technology, would also greatly ease the problem of meeting more stringent standards. This assertion can be quantified somewhat by noting that 39 foreign and 37 domestic vehicles would have been certified at levels below the Federal 1977 Emissions Standard if no correction had been needed for the deterioration factor.^{4.1}

The last two columns in Table IV-2 indicate what number (and percentage) of these vehicles could meet a standard in which only HC or only CO is reduced below the present California Standard. The data in these two columns should not be construed to imply that HC is easier to control than CO. What it does reflect is the greater average safety factor currently used for the HC control technology. The data further indicate that, while HC and CO control are closely coupled, nevertheless, relaxing the standard for either one will help ease the problem of meeting the standard for a number of vehicles.

3. Two Oldsmobile Fleets Tuned to the Federal 1977 Emissions Standard

The ability of cars equipped with current catalyst technology to meet the Federal 1977 Emissions Standard has been more effectively demonstrated by two fleets of Oldsmobiles operated by the California Highway Department. Both fleets are equipped with GM under-floor oxidizing catalytic converters and various engine modifications. The first group of 13 had no air pumps and after two years of service had accumulated

about 25,000 miles, while the second group was equipped with air pumps and had accumulated almost 14,000 miles in one year of service as of August 1974.^{4.2}

A summary of the emissions data from these vehicles is given in Table IV-4. There appears to be little evidence of deterioration for HC and NO_x and only a small deterioration for CO. The trend thus far exhibited by the emissions of these vehicles suggests that the Federal 1977 Emissions Standard will be met for use up to 50,000 miles by many of these vehicles. It should further be noted that information from these fleets and from the 1975 production models should enable the manufacturers to do a better design job in 1977 and thus meet the presently mandated standards with a minimum of risk to themselves and to the consumers. A somewhat higher sticker price and a 5% poorer fuel economy, on average, than vehicles now meeting the Federal 1975 Emissions Standard is, however, likely.

The fuel economy in miles per gallon was determined using the EPA test procedure at 16,022 miles for the 13-car fleet and at 8,620 miles for the 12-car fleet; the results were 9.4 ± 0.4 mpg and 10.2 ± 0.4 mpg, respectively. It is dangerous to draw conclusions on fuel economy from this limited data base. Nevertheless, it is interesting to compare this to the 10.1-mpg average fuel economy we have assumed for 1973-1974 vehicles in the 5,000-lb class.^{4.3} An analysis of the 1975 certification data by Austin and Hellman^{4.4} suggests that the average fuel economy of a 5,000-lb vehicle in 1974 was 14% worse than in the 1975 model year. Thus, we might conclude that the best of the two Oldsmobile fleets calibrated to the Federal 1977 Emissions Standard has a fuel economy 13% poorer than the average 5,000-lb vehicle meeting the 1975 standards. There is good reason to believe, however, that this can be improved substantially using improved 1975 technology and calibration procedures.

B. Mixture Control

The correct control and preparation of air/fuel mixtures is essential

TABLE IV-4

UNDER-FLOOR CONVERTER FLEET
CALIBRATED TO MEET 1977 STANDARDS

California Division of Highways
Exhaust Emissions Test Summary

13 OLDSMOBILES (5,000 lb) Without Air Pumps

Average Test Mileage	No. of Cars ³	1975 EPA g/mi ¹		
		HC	CO	NO _x
194	13	0.19	1.90	1.75
4,108	13	0.20	2.22	1.86
8,222	13	0.24	2.14	1.84
12,296	5	0.25	2.83	1.75
16,022	13	0.24	2.87	1.79
20,535	5	0.23	2.13	1.72
24,976	3	0.21	3.16	1.93
24,950 ²	12	0.23	3.12	1.86
29,635 ²	2	0.19	3.23	2.20

12 OLDSMOBILES (5,000 lb) With Air Pumps

Average Test Mileage	No. of Cars ³	1975 EPA g/mi ^{1,2}		
		HC	CO	NO _x
230	12	0.30	1.91	1.48
4,426	12	0.31	1.98	1.62
8,820	12	0.31	2.21	1.72
13,857	12	0.35	2.50	1.58

¹Official Federal Test Procedure.

²A slave canister test procedure was used to save time. It gives a lower CO emissions which we have adjusted in these tables by adding 1 g/mi CO to the levels actually reported. HC and NO_x emissions are unchanged.

³Not all cars were available for testing at each mileage.

Source: Reference 4.2

in determining vehicle emissions, fuel economy, driveability, and starting characteristics. The carburetor, which is used predominately on automobiles produced in the United States, has been improved in its ability to maintain air/fuel ratio control. While these improvements have contributed to the reduction of emissions to present levels, further reductions require substantial additional improvements in the control of mixture ratio. Conventional carburetors probably are not adequate to do the task, so that advanced carburetors or other mixture-control systems are required.

1. Carburetors

In simple carburetors, fuel flows from a jet located in the throat (Venturi) of the carburetor. These devices tend to give rich mixtures at high flows and/or lean mixtures at low flows. In modern carburetors, better mixture control is obtained by using multiple throats and fuel orifices to provide better flow conditions over the full operating range of the engine. These carburetors can control air/fuel ratios to within about 5%. However, the mixtures actually delivered to individual cylinders will vary much more because of problems of manifold design, transients in operation, liquid impingement on manifold walls, and ambient changes in altitude, temperature, and humidity. As a result, mixture ratios may vary by as much as $\pm 20\%$ of nominal values; such variation is grossly inadequate for the maintenance of low emissions, fuel economy, and good driveability. These problems are accentuated during cold starts and under idle or low-load operation because air flows are low and large fuel droplets result.

One form of improvement is provided by the variable-Venturi and constant-depression carburetors. These more complex carburetors provide higher throat velocities, insuring better fuel-flow control and atomization over the range of engine operating conditions. Most carburetor companies appear to be working on some form of such improved carburetors.

These improvements are not expected to be adequate for the requirements of the three-way catalyst systems, which require very precise air/fuel ratio control. Most, perhaps all, dual-catalyst and lean-burn systems also require mixture control better than that delivered by conventional carburetors.

Sonic carburetors, particularly the Dresser sonic-flow carburetor, show promise to improve atomization, mixture control, and mixture distribution. The Dresser carburetor offers positive air-flow control through a choked-flow diffuser, precise air/fuel ratio control, low-pressure drop, fine droplet atomization, and good mixing. The ability to control homogeneity allows lean operation of the engine and reduced emissions, even without other emissions-control devices. Such mixture-ratio and mixture-distribution control makes operation of a "lean-burn" engine and realization of the gains of fuel-lean operation discussed in Section III.C-2 possible. Another type of carburetor, made by Autotronics, provides improved mixture control by promoting droplet breakup through impingement of the fuel on an ultrasonic vibrating plate. One or more of the above class of carburetors may be in limited production by the 1978 model year. Data on some of these systems is given in Table IV-5.

2. Fuel Injection

The first electronic fuel-injection systems, developed about 15 years ago, determined air flow electronically and injected the appropriate amount of fuel. These systems have offered better cylinder-to-cylinder mixture distribution, especially for engines with poorly designed intake manifolds or difficult fuel-induction problems. Such systems have improved maximum power but have been limited in their application by high cost. Electronic fuel injection alone does not have any advantage over a well-carbureted engine.

Current electronic and mechanical fuel-injection systems employ air-mass-flow sensors. A temperature sensor enables fuel enrichment during start-up and leaning of the mixture once the engine is warm. The mechanical fuel-injection system is simpler in operation and lower in cost than electronic fuel injection. Mechanical systems are comparable

TABLE IV-5
Performance of Mixture-Control Systems Without Catalysts

Vehicle	Ref. ¹	Mixture Preparation System ²	Emissions ²		Fuel Economy ³ MPG	Status ⁴
			HC	CO NO _x		
Dodge Monaco, 1973 360 CID	(5.2)	Variable Venturi Carburetor	1.48	10.28 1.8	11	PP
Dodge 1974 4,500 lb, 360 CID	(5.2)	Hot-box manifold thermo-quad Carburetor, EGR	1.33	7.80 2.76	10.7	PP
Dodge 1974 4,500 lb, 360 CID	(6)	Above + lean reactor	0.5	5.0 1.4	10-15% gain over '74	PP
Volkswagen, 1.6 liter	(5.3)	L-Jetronic	1.16	7.1 1.22	17.8	P
Saab, 2 liter, 3,000 lb	(5.3)	Standard Carburetion	1.9	40.7 2.4	17.7	P
		K-Jetronic, closed-loop	0.9	8.14 2.2	19.3	PP
Saab, 2 liter, 3,000 lb	(5.3)	D-Jetronic	1.18	40.9 2.2	16	P
Chevrolet, 1973 Monte Carlo 350 CID, AT (GM Test)	(6)	Dresserator No EGR	0.85	3.9 1.9	11.5	R
Ford, 1971 Galaxie 351 CID, A1 (Ford Test)	(6)	Dresserator No EGR	0.70	4.2 1.9	10.7	R
Ford, 1973 Capri 2,600 cc (EPA Tests)	(6)	Dresserator	0.7	5.8 1.2	18.2	R
Chevrolet, 1973 Monte Carlo 350 CID, AT (EPA Tests)	(6)	Dresserator	1.1	5.1 1.6	12.8	R
Ford, 1971 Galaxie 4,500 lb, 351 CID	(6)	Dresserator + thermal reactor (enlarged exhaust manifold)	0.3	4-5 1.2-1.7	11	R

¹ All data are taken from the indicated Sections of the "Consultant Report to the Committee on Motor Vehicle Emissions on Emission Control of Engine Systems," Reference 4.5.

² CVS-CH test procedure, low-mileage measurements, uncorrected for deterioration.

³ EPA "city mileage" based on CVS-CH test.

⁴ Status: P is production; PP is preproduction; and R is research.

to electronic fuel injection in emissions reduction and fuel economy improvement.

3. Feedback Systems

The air/fuel ratio is influenced by many parameters, only a few of which are sensed by present fuel-control systems. Such open-loop fuel control cannot be correct under all conditions of vehicle operation. A closed-loop system which monitors the composition of the exhaust or an engine output parameter can maintain the air/fuel ratio within correct limits by constantly supplying a corrective signal to the primary air/fuel metering device. Such systems are in a sense self-maintaining in that they do not go out of adjustment.

Several companies (e.g., Bosch and Bendix) are actively working on the combination of an oxygen sensor with electronic fuel injection to provide a closed-loop, feedback-control system. Near stoichiometric, this particular sensor produces an output which varies strongly with exhaust-gas composition and provides the form and degree of mixture control necessary for the operation of three-way-catalyst, emissions-control systems. Such precise control of air/fuel mixture generally reduces fuel consumption over conventional carbureted systems. The feedback-control principle also has been employed with an electronic carburetor, the main incentive being lower cost and the ability to utilize present domestic production capability. To realize full benefit, good manifold distribution must be insured with the carbureted systems, suggesting the necessity of using a variable-Venturi, sonic-flow, ultrasonic, or hot-spot carburetor.

The use of feedback-mixture-control systems for the conventional spark-ignition engine has been demonstrated. These systems constitute a substantial improvement in mixture control. They are essential to the operation of some emissions-control systems but also alone provide improvements in emissions, fuel economy, and driveability. They have potential application to nonconventional as well as the conventional

engines for which they were developed. The performances of several carbureted, fuel-injected and feedback-mixture-control systems without catalysts are summarized in Table IV-5.

4. Exhaust Gas Recirculation (EGR)

The recirculation of exhaust gas back into the intake system is used for the control of oxides of nitrogen through reduction of the peak combustion temperature. The exhaust gas acts as an inert substance. The use of water for the same purpose has been investigated but adds the complexity of an additional fluid system to the engine. Small amounts of EGR have been used to improve knock resistance and also can improve fuel economy. When EGR is used in the amounts required for NO_x reduction, increased fuel consumption and reduced driveability are encountered. For the attainment of NO_x levels below about 1 g/mi, loss of fuel economy is so great as to make the use of EGR unattractive, even for small cars for which NO_x emissions levels are already low because of low exhaust flows. There is some tradeoff between NO_x and HC control on oxidation-catalyst-equipped cars. Higher engine HC levels allow partial compensation for the adverse effects resulting from the control of NO_x through exhaust gas recirculation. Most EGR systems are now of the proportional type which adjust exhaust gas recirculation rates according to engine operating conditions so as to maximize NO_x reduction and minimize losses of fuel economy and driveability.

5. Fuel Modification

Evaporation of the fuel, usually after passing through the carburetor or fuel-injection system, enhances cold-start and good-mixture distribution. Many of the 1975 vehicles use a quick-heat manifold or early-fuel-evaporation device to help during cold start. Several companies are experimenting with evaporative heaters which operate continuously. The Ethyl Corporation Hot-Box Manifold and the Shell Vapipipe

systems are two such devices which have been applied to lean-burn engines. Substantial emissions reductions have been obtained without the use of catalytic reactors.

A more drastic alteration of the fuel involves the use of an onboard, catalytic fuel reformer that converts the gasoline in a partial oxidation process to a gaseous mixture consisting primarily of hydrogen and carbon monoxide. The engine can be run entirely on such a reformed fuel or on a mixture of the gasified fuel and liquid gasoline. The gains from such a system are closely related to those noted for a lean-burn engine. The presence of hydrogen is believed to assist in the combustion of lean mixtures by increasing flame speed and flammability limits. This system is in the early research and development stage.

A more direct method of fuel modification is to employ a fuel other than gasoline. If alternative fuels come into significant use, fuel availability related to energy management is likely to be the controlling factor, rather than air pollution. Some alternative fuels do possess definite emissions-reduction advantages which may assist in meeting emissions standards but would not insure their adoption. The more important question, therefore, appears to be related to the effect that the imposition of new motor-vehicle fuels would have upon engine emissions rather than what fuels should be promoted for the purpose of reducing engine emissions. See Section IX for further discussion of fuel additives and alternative fuels.

The development of new fuel sources, especially coal and oil shale, will necessarily produce changes in the composition of motor fuels. The use of methyl fuel (a blend of alcohols containing mostly methanol), either in a blend with gasoline or as a pure fuel, has been proposed as a means of extending fuel resources. Methanol-gasoline blends have exhibited slightly reduced emissions, usually attributable to a changed air/fuel ratio.

Pure hydrogen produces an extremely low pollutant emission but is not anticipated to come into use as a motor fuel because of non-

availability, distribution, and handling difficulties. Alternative fuels are not seen as playing a major role during the next five years. The development of new fuel resources may lead to new motor fuels and the impact of these fuels on motor-vehicle emissions should be monitored. A summary of the performance of the systems employing fuel modification is provided in Table IV-6.

C. Combustion Modification

The flexibility to produce major changes in the combustion process within conventional engine combustion chamber design is limited. As a consequence, approaches which have sought to modify the combustion process in a substantial manner generally have led to substantially different engine configurations and are discussed in later sections, particularly under the heading of stratified-charge engines. Some modification to existing combustion chambers has proven useful in reducing emissions.

1. Spark Timing

The use of spark retard has been employed to reduce both hydrocarbons and oxides of nitrogen. Unfortunately, fuel economy also is reduced. The control of hydrocarbons by oxidation catalysts and oxides of nitrogen by exhaust gas recirculation on 1975 cars allows spark advance and concomitant recovery of the fuel economy losses associated with spark retard used for emissions control on earlier model years.

2. Compression Ratio

Lowering of the compression ratio reduced both hydrocarbons and oxides of nitrogen, but with a loss of fuel economy of 4% to 5% in going from a 9 to 1 to an 8 to 1 compression ratio. In the conventional engine, however, the current compression ratio is knock limited and fixed by the requirement that the vehicle be able to use unleaded 91 research octane

TABLE IV-6

Performance of Fuel Modification Systems, Primarily for Lean Operation

VEHICLE	EMISSIONS SYSTEM	EMISSIONS g/mi			FUEL ECONOMY mi/gal	OTHER PERFOR- MANCE	STATUS ¹
		HC	CO	NO _x			
Morris, Marina, ³ 1.8L, MT, 2,500 lb	Shell vapors, A/F = 16.5 No other emissions controls	4.9	5.9	15	22.6	starting or heat-up problem	R
Chevrolet, Impala ⁴ 350 CID, AT, 4,500 lb	JPL, H ₂ addition unmodified bottled H ₂	2.29 2.6	43.9 1.6	1.75 0.52	9.3 14.0 ²		R
GM, Intermediate 19 ³ 455 CID, AT, 3,500 lb	Hydrogen supply- mented fuel constant H ₂ flow constant H ₂ frac- tion	2.6 3.1	5.6 3.3	1.3 0.39		power loss power loss	R
EXXON Research ⁴ 1973 Calibration	Gasoline (base line)	1.1	21	2.6		vapor-pressure problems	P
351 CID	Gas & 15% Methanol	1.1	8	1.7		phase- separation problems	R
1975 Calibration	Gasoline (base line)	0.10	0.3	2.6		vapor-pressure problems	P
351 CID (with catalyst)	Gas & 15% methanol	0.10	0.4	2.3		phase- separation problems	R

¹ P - production; R - research² "mi/gal" for bottled gas based on BTU equivalent³ Reference 4.6⁴ Reference 4.7

number fuel, not from direct consideration of HC, CO or NO_x emissions. The recovery of fuel economy through increasing compression ratio within the constraints of fuel octane availability and emissions is an elusive and difficult task.

3. Combustion-Chamber Geometry

Some relatively minor modifications to the combustion-chamber geometry, such as the location of the spark plug, positioning of the piston rings, elimination of crevices, and control of turbulence, do affect engine emissions. These approaches are in the category of "cleaning up" the combustion-chamber design and have yielded emissions reductions. Substantial additional gains, however, require basically different engine configurations.

4. Ignition Systems

To meet even current hydrocarbon emissions levels, the engine cannot tolerate misfire or a failure to ignite the mixture, even occasionally. Higher-energy ignition systems give a greater assurance of ignition. Breakerless systems offer increased durability and, therefore, reliability over the lifetime of the car. Some work has been done on the use of multiple spark plugs, multiple sparks from a single spark plug, and continuous ignition systems. Since reliable ignition can be insured on conventional engines without going to such lengths, their potential application is more likely to be on lean-burn systems, which have more difficult ignition problems.

D. Exhaust Treatment

The use of exhaust-treatment devices has been applied successfully to meet hydrocarbon and carbon monoxide emissions standards. The use of reduction catalysts, either three-way or dual, appears to be the most likely approach to meeting stringent oxides of nitrogen emissions standards

with conventional engines. Two additional exhaust-treatment devices have been used or proposed--thermal reactors and particulate traps. A variety of combinations of exhaust-treatment devices have been proposed to overcome problems of starting or of obtaining the degree of control necessary.

1. Thermal Reactors

Thermal reactors have been used to promote the gas-phase oxidation of hydrocarbons and carbon monoxide. Excess oxygen and high temperatures are required to insure efficient oxidation. Early versions have required a fuel-rich exhaust and air injection to insure that high thermal-reactor temperatures could be maintained. Such a system was particularly suited to the rotary engine because of its inherently high hydrocarbon exhaust levels. Unfortunately, the requirement to operate the engine fuel rich necessarily results in decreased fuel economy. Better design of the thermal-reactor system appears to allow use of a lean thermal reactor which would not suffer the fuel economy penalty of the rich thermal reactor. Air injection might still be required to insure that the oxidizing mixture is available at all engine operating conditions.

Many lean-burn engines also include a simple thermal reactor, often no more than a somewhat enlarged, thermally insulated exhaust manifold. Because of the lower exhaust temperatures of the lean-burn engines, thermal reactor performance is limited but usually adequate to give approximately a 50% reduction in hydrocarbons. Since the introduction of the oxidation catalyst, thermal reactors are now found primarily on rotary, lean-burn, and stratified-charge engines.

2. Catalytic Reactors

There are three general categories of catalytic reactors for emissions control. The catalytic system in use on most 1975 cars is a

noble-metal oxidation catalyst. A reduction catalyst is proposed for the removal of the oxides of nitrogen. These two reactors may be used in series in a dual-catalyst system. The single catalyst that removes HC, CO and NO_x simultaneously is known as a three-way catalyst.

3. Oxidation Catalysts

Noble-metal catalysts, which contain platinum, paladium, and/or rhodium supported on oxide pellets or monolithic substrates, have been demonstrated to meet the 0.41 g/mi HC and 3.4 g/mi CO standards for 50,000 miles. No base-metal oxidation catalysts have demonstrated adequate durability.^{4.8}

Noble-metal oxidation catalysts increase the amount of sulfur emitted as SO₃ (which is rapidly converted to sulfuric acid in the presence of water) from less than 10% to 15%-60% depending on the temperature and amount of oxygen present.^{4.9} The use of an air pump causes higher SO₃/SO₂ ratios than without. The catalysts absorb SO₃ at low temperature but then release it during high-temperature operation. The oxidation catalysts operate at lower temperatures than thermal reactors and, therefore, effectively decouple emissions control from engine performance allowing the tuning of the engine for improved fuel economy. This can result in fuel economy gains of as high as 20% over comparable 1974 vehicles.

Noble-metal oxidation catalysts have demonstrated durability for at least 50,000 miles under EPA certification test conditions and allow improvement on fuel economy over previous hydrocarbon and carbon monoxide control systems. The oxidation catalysts are deactivated by the presence of compounds containing lead, bromine, and phosphorous at levels above those of EPA durability fuel and oil specifications. Recovery of catalyst activity from occasional exposure to these compounds has been observed. Early problems with cracking, burnout, and attrition appear to have been minimized through improvements in ignition systems

and catalyst packaging. Total ignition failure at speeds above about 50 mph is likely to result in reactor temperatures sufficiently high to deactivate permanently the catalysts or to damage the substrate and/or container. Only limited data exist on the performance of these systems after 50,000 miles or under conditions of actual use and owner maintenance. See Section VIII for further discussion of in-use durability.

All of the noble metals must be imported, mainly from Russia and South Africa. Their use in catalytic converters will more than double the requirements for these metals in the United States in 1975 and 1976 and somewhat heavier loading is expected to be necessary to meet the lower HC and CO levels of the Federal 1977 Emissions Standard. The use of nickel and chromium in the catalyst containers increases our overall use by 0.1% to 1%. This is, however, a significant added requirement on the limited supply of these materials, which come primarily from foreign sources.^{4.9} The three-way and dual-catalyst systems are both expected to use up to twice as much noble metal per car as the present oxidizing catalysts, and the dual catalyst could double the requirements for chromium and nickel for the housing and increase our use of nickel by as much as 10% if a base-metal reducing catalyst is used.

Oxidation catalysts essentially eliminate the emissions of polynuclear aromatics, olefins, and partially oxidized compounds such as phenols, aldehydes and mercaptans; that is, these reactive hydrocarbons are eliminated to a much greater extent than the total hydrocarbons. By requiring use of unleaded gasoline, the catalysts also will result in a decrease in automotive particulate emissions attributable largely to lead compounds.^{4.9}

Loss of noble metals from exhaust systems is not a significant problem under normal operating conditions. The total amount of noble metal per vehicle is less than 0.1 oz and during 50,000 miles of operation less than 10% of this material is lost. Nonetheless, ambient monitoring of emissions for their content of noble metals, lead, sulfur, and phosphorus is recommended so that impact of the introduction of catalyst-equipped cars can be assessed through the increase or decrease of these compounds.^{4.9}

4. Reduction Catalysts

Catalyst systems able to meet the Federal 1978 Emissions Standards (0.41/3.4/0.4 g/mi) for 50,000 miles without a catalyst change have not been demonstrated. Several systems have been demonstrated which are close to meeting the Federal 1978 Emissions Standards for 25,000 miles, as shown in Table IV-7. Due to uncertainties in the future NO_x standards, less effort is being applied to research and development on these systems than would otherwise be the case.

The reduction catalysts require a fuel-rich mixture and, therefore, suffer a fuel economy penalty, although this may be minimized by operating only slightly to the fuel-rich side of stoichiometric. Reduction catalysts cannot be used for NO_x control on engines that produce fuel-lean exhaust products (for example, the lean-burn, stratified-charge, and diesel engines).

The air/fuel ratio must be controlled carefully for satisfactory operation of the NO_x catalyst. A too highly reducing atmosphere will lead to the formation of ammonia and an inadequately reducing atmosphere will prevent the reduction of NO_x . Lean transients must be avoided when the catalyst is at operating temperature, as they lead to excessive temperatures and potential failure. An upstream oxidation catalyst or thermal reactor is employed in some systems to protect the reduction catalyst from excess oxygen.

The combination of a reduction catalyst followed by an oxidation catalyst is referred to as a dual-catalyst system. Improved carburetion to achieve better air/fuel ratio control is required. During the start-up phase, air is injected upstream of the reduction catalyst, which is mounted near the engine exhaust manifold. The reduction catalyst acts as an oxidation catalyst during the start-up period. As a minimum configuration, a reduction catalyst followed by air injection followed by an oxidation catalyst is used. In the Gould system an additional small,

TABLE IV-7

Experimental Emissions Data from Dual-Catalyst Systems

<u>Vehicle</u>	<u>Mileage</u>	<u>HC</u>	<u>CO</u>	<u>NO_x</u>
1. Ford Galaxie, 351 CID	0	0.8	2.9	0.6
	9,000	1.2	6.2	0.7
2. Ford Galaxie, 351 CID	0	0.7	3	0.7
	10,000	0.7	3.4	0.8
	22,000	1	7	1
3. Ford Galaxie, 400 CID	0	0.6	0.9	0.4
	8,000	1	1.5	0.5
	12,000	1.2	2	0.7
4. General Motors, 5,000 lb	0	0.36	1.9	0.41
350 CID, EGR	3,000	0.41	2.4	0.56
5. General Motors, 5,000 lb	0	0.31	2.8	0.24
350 CID, EGR	8,000	0.38	3.4	0.24
	12,000	0.94	4.4	0.38
	16,000	0.84	7.6	0.34
	20,000	0.66	3.4	0.36
	24,000	0.8	6.8	0.36
6. British Leyland, Austin Marina	0	0.39	1.32	0.29
	6,740	0.53	1.71	0.27
	10,720	0.58	1.7	0.64
7. British Leyland, Austin Marina	0	0.15	0.67	0.45
	10,875	0.38	1.8	0.85
8. British Leyland, Austin Marina	0	0.19	2.49	0.35
	6,600	0.36	1.51	0.23
9. Nissan, 119 CID, Datsun, 2,750 lb	0	0.09	1.08	0.33
	4,600	0.27	0.73	0.39
	11,700	0.30	0.93	0.48
	20,700	0.39	1.67	0.68
10. Nissan, 119 CID, Datsun, 2,750 lb	0	0.21	1.38	0.30
	11,800	0.33	1.1	0.31
	18,300	0.57	4.07	0.39
11. Toyota, 2,500 lb, 1.6 liter	0	0.11	1.89	0.43
	5,000	0.17	1.12	0.49
12. Datsun, 2,500 lb	5,600	- ¹	3.1	0.35
No EGR, MT	10,249	-	1.9	0.35
Gould System (Tests at Gould)	15,381	-	1.9	0.38
	25,580	-	3.2	0.38
(EPA Confirmation Test)	25,580	0.98	2.9	0.41
21.8 mpg at EPA				
13. 1971 Pontiac Catalina	0	0.085	3.0	0.36
5,000 lb	18,483	0.40	2.7	0.38
Questor System	23,142 ²	0.23	1.6	0.62
(8.2 mpg reported is 15%	35,946	0.16	3.0	0.42
to 20% poorer than for 1974)	50,024	0.29	3.0	0.28

¹Emissions for HC are not listed due to inaccurate measurement.²Catalyst changed at 23,142 miles.

Source: All data taken from Reference 4.10

noble-metal catalyst is provided upstream of the reduction catalyst. The Questor system uses a rich thermal reactor, followed by a reduction catalyst, which in turn is followed by a second thermal reactor. Performance of these systems is summarized in Table IV-7.

5. Three-Way Catalytic Converters

Simultaneous control of all three pollutants in a single catalytic converter is possible, but precise air/fuel ratio control of about 0.5% is required. Simple carburetion is not adequate and an oxygen-sensor feedback-control system is required. Most catalysts presently under investigation contain noble metals: platinum, palladium, rhodium, and, possibly, ruthenium. Although early oxygen sensors had very poor durability, several manufacturers now have sensors which can be guaranteed for 12,000 miles or more. Bosch has reported 20,000-mile durability of a three-way catalyst with an oxygen-sensor feedback-control system that meets the stringent 0.41/3.4/0.4-g/mi emissions standard for HC/CO/NO_x in a 4-cylinder car.

The meeting of the Federal 1978 Emissions Standard has been demonstrated at low mileage by three-way-catalyst, oxygen-sensor, feedback-control systems using one of three different mixture-control systems: electronic fuel injection, mechanical fuel injection, or electronic carburetion. Some data on these systems are listed in Table IV-8. In all cases, fuel economy and driveability are good. A strong commitment is required, however, to insure that these systems will be ready by 1978. The most significant remaining difficulty for introduction of this technology is the assurance of catalyst durability. Thus far, no system has achieved the Federal 1978 Emissions Standards for more than 25,000 miles without a catalyst change.

6. Traps and Other Devices

Several particulate trap systems have been demonstrated as means for removing lead particulates from conventional engine exhaust. Although

TABLE IV-8. Performance of Three-Way-Catalyst

VEHICLE	EMISSIONS SYSTEM	EMISSIONS g/ml			FUEL ECONOMY mi/gal	OTHER PERFOR- MANCE	MANUFACTUR- ABILITY	STATUS*
		HC	CO	NO _x				
Mercedes-Benz 4.8L	Daimler Benz, O ₂ Sensor, L-jetronic FI low mileage	0.4	1.8	0.4	9.4		1977 1978-U.S.	R
Vehicle R 1.9 L, MT, 2,300 lb	Robert Bosch, O ₂ Sensor, L-jetronic FI 20,000 miles	0.3	1.7	0.3	18.7		"	PP
Volkswagen	VW, O ₂ Sensor L-jetronic FI low mileage	0.3	1.2	0.2			"	R
GM, Chevrolet 350 CID, AT, 4,500 lb	O ₂ Sensor, EFI low mileage	0.56	5.1	0.96	11.5		1978	R
GM, Chevrolet Vega 3,000 lb	O ₂ Sensor, EFI low mileage	0.23	2.6	0.3	20.4		"	R
Ford 351 CID, 5,000 lb	Ford, O ₂ Sensor, EFI a) Fresh catalyst b) 100 hr catalyst	0.1 0.11	2.0 0.68	0.5 1.34			"	R
Saab	Saab, O ₂ Sensor K-jetronic FI	0.1	1.7	0.21	19.5		1977 1978-U.S.	R
Volvo	Volvo, O ₂ Sensor, K-jetronic FI	0.25	0.8	0.25	16.0		"	R
Audi	K-jetronic FI, O ₂ Sensor	0.28	1.0	0.4			"	R
GM 350 CID, AT, 4,500 lb	GM, O ₂ Sensor IFC Carburetor low mileage	0.17	5.5	0.69	11.5	Good Drive- ability and power	1978	R
GM 350 CID, 4,500 lb	GM, O ₂ Sensor Mod. Quadrajet carb. low mileage	0.28	4.85	0.54	11.7		1977	R

*R - research, PP - preproduction

Source: All data taken from Reference 4.11

the elimination of lead from gasoline obviates this potential need, such devices might be required for alternative engines with particulate-emissions problems, such as the diesel, should a particulate-emissions standard be enacted. Present traps tend to be limited, however, by their ineffectiveness with particles under about one micron. Particles in this smaller size range have the greater physiological effect when respired.^{4.9}

V. ALTERNATIVE AUTOMOBILE ENGINES FOR THE NEAR- AND THE LONG-TERM

Three light-duty, motor-vehicle engine types not now produced domestically could be mass-produced domestically by 1980 if adequate incentives exist. These are various types of stratified-charge engines, the diesel and the rotary engines. Other promising alternatives (discussed in the last part of this section) could not be mass-produced economically until 1980 at the earliest.

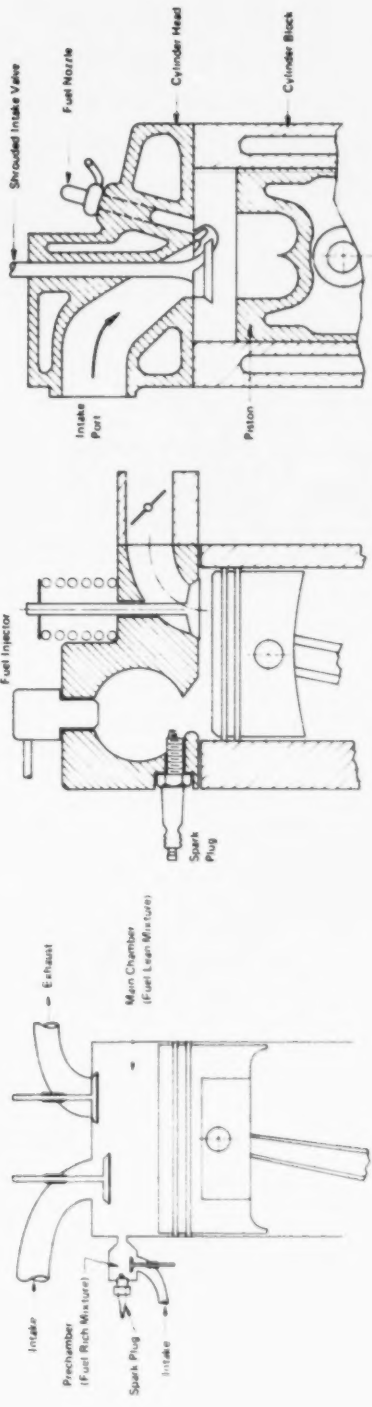
A. Stratified-Charge Engines

Like the conventional engine, the stratified-charge engines are Otto cycle, spark ignition, and, mostly, gasoline fueled. Their distinguishing characteristic is that the air/fuel mixture is not uniformly distributed in the combustion chamber but is distributed into fuel-rich and fuel-lean regions. Some versions of these engines are quite similar to conventional engines and, therefore, have the attractive feature of being able to draw upon existing conventional engine technology and manufacturing facilities. In several different configurations, they have demonstrated the ability to combine low emissions with improved fuel economy and good driveability.

No commonly accepted classification of these engines exists. The diesel engine also is a stratified-charge engine, but compression rather than spark ignited and, therefore, is discussed separately. For convenience, the discussion of these engines has been divided into three categories: torch ignition (with prechamber), divided chamber, and open chamber. Examples of each type of stratified-charge engine are pictured in Figure V-1.

1. Torch-Ignition Engines

The torch-ignition engine closely resembles a conventional spark-ignition engine with the spark plug replaced by a small prechamber with its own spark plug. The function of the prechamber is to ignite a lean, homogeneous mixture in the main chamber. The mixture in the main chamber is generally prepared with a conventional carburetor. The



Small Volume Prechamber (Torch Ignition) Honda CVCC

Divided Chamber Ford

Open Chamber Texaco TCCS

FIGURE V-1 Stratified-Charge Engine Configurations.

Source: Reference 5.1

prechamber mixture, which is usually fuel rich, may be formed by a small carburetor or by fuel injection. Air in the prechamber may be delivered with the fuel or from the main chamber. The volume of the prechamber is 5% to 15% of the clearance volume of the main chamber. These engines are also known as "small-volume prechamber engines," "three-valve prechamber engines," and "jet-ignition engines." Historically, engines associated with the names Ricardo, Schlamann, Brodersen, Heintz, and Nilov were the predecessors of the CVCC (compound vortex-controlled combustion) engine developed and now manufactured by Honda.

This engine, in a 2,000-lb vehicle, has met the 1977 emissions standard (0.41/3.4/2.0 g/mi) without catalytic reactors, air injection, or exhaust gas recirculation (Table V-1). Little deterioration of emissions levels was noted at 50,000 miles. The Honda CVCC engine does include a small lean-thermal reactor. Honda has demonstrated the success of this design in a variety of engine sizes, including a large V-8 engine. Apparently because of the success of Honda, virtually every automobile manufacturer, worldwide, has or is developing a CVCC engine. Most of this work, some of which is in cooperation with Honda, confirms Honda's results. Results to date indicate that the attainment of 0.4 g/mi NO_x requires the use of exhaust gas recirculation and results in a substantial loss of fuel economy, as shown in Table V-1. The control of hydrocarbon emissions also results in a loss of fuel economy. Fuel economy appears to be comparable to a catalyst-equipped conventional engine at the 0.41/3.4/2.0-g/mi emissions levels. Performance data for several CVCC engines are given in Table V-1.

The emissions and fuel economy characteristics of these vehicles are uncommonly uniform. Emissions levels show little or no change over at least 50,000 miles of operation. Honda reports no durability or maintenance problems associated with this three-valve engine which would distinguish it from the conventional two-valve spark-ignition engine. The cost increment over a conventional engine of intermediate size, without emissions controls, is estimated to be about \$200. These vehicles were

TABLE V-1
Performance of Torch-Ignition, Stratified-Charge Engines (Honda CVCC)

Vehicle	Emissions System	Emissions g/mi			Fuel Economy mi/gal	Status*
		HC	CO	NO _x		
Chevrolet, 5,000 lb	Honda CVCC Conversion	0.23	2.9	1.7	11.2	R
Honda, CVCC 1.5L, NT, 2,000 lb	CVCC	0.60	4.9	1.38	28.4	P
	1975 sys. 1977 sys.	0.23	2.2	1.15	25.2	PP
Honda, CVCC 2.0L, NT, 2,000 lb	CVCC	0.17	2.3	0.89	22 - 24	PP
	1977 sys. 1978 sys.	0.33	3.0	0.38	19.0	R
Honda, CVCC 2.0L, NT, 2,000 lb	CVCC	0.18	2.12	0.89	22.1	PP
	low mileage 50,000 mi	0.24	1.75	0.65	21.3	PP

*P - production; PP - preproduction; R - research

Source: Reference 5.1

first marketed in Japan during the beginning of calendar year 1974 and are planned for export to the United States for sale near the beginning of the 1975 model year.

The Honda engine, as tuned to meet the 1975 California Emissions Standards, appears to have a research octane number requirement of 77-85 and, therefore, is easily satisfied with present 91 RON commercial unleaded gasolines. The engines are lead tolerant and have completed Federal certification using fully leaded gasolines. However, because of the low octane requirement, the economic benefit of the lead alkyls is not realized. Maximum compression ratio appears to be limited by hydrocarbon emissions control rather than by available fuel octane quality.

Although a number of engines related to the Honda design are under investigation, none appears to surpass the combined emissions, fuel economy, and driveability performance of the Honda. It is anticipated that additional performance could be realized through improvements in the carburetor and fuel distribution system.

2. Divided-Chamber Engine

As the prechamber volume approaches the clearance volume in size, the engine falls into the divided-chamber category. Other engine names in this group are "divided-chamber staged-combustion engines," "large-volume prechamber engines," and "blind-fuel-injected prechamber engines." Direct-fuel-injected versions of these engines appear to offer NO_x control advantages over both the torch-ignition and open-chamber engines. (Direct injection is here used to define fuel-injection directly into the cylinder, as opposed to indirectly via the intake manifold.) Work on engines in this category remains in the developmental stage. The control of hydrocarbon emissions is strongly dependent on fuel injection spray characteristics. Performance characteristics of representative engines are shown in Table V-2.

TABLE V-2
Performance of Divided-Chamber, Stratified-Charge Engines

Vehicle	Emissions System	Emissions			Status*
		HC	CO	NO _x	
		g/ml			
VW 2.0L,	Direct prechamber injection, 9:1 CR, thermal reactor	1.0	4.0	1.0	R
VW 1.6L,	Direct prechamber injection, 8.4:1 CR	2.0	5.0	0.9	R

*R - research

Source: Reference 5.2

3. Open-Chamber Engines

The open-chamber stratified-charge engines employ a single combustion chamber with direct injection of the fuel. In many respects, they are similar to diesel engines, but they are spark ignited. The Ford (PROCO) and Texaco (TCCS) versions of this engine type are the most advanced. The most notable feature of these engines is their superior fuel economies which approach those of diesel engines. Control of hydrocarbon and carbon monoxide emissions requires the use of an oxidation catalyst. The Texaco version possesses a multi-fuel capability and provides comparable emissions levels and fuel economy whether operated on gasoline, diesel fuel, or kerosene (jet fuel) as shown in Table V-3.

EGR is used for NO_x control. In meeting the 0.4 g/mi NO_x emissions standard, a fuel economy loss is incurred which nearly cancels the inherent fuel economy advantage of the basic engine. These engines remain in the development stage. Hercules Engine Company is developing a preproduction prototype of the Texaco engine for the U.S. Army.

B. Diesel Engines

The diesel engine has been widely used in heavy-duty truck applications but has found only limited sales in the United States automotive market. The diesel engine has excellent part-load performance. Extensive experience in Europe with diesel-powered taxicabs and light trucks for city driving show fuel consumption about half that of comparable gasoline engine vehicles. Because of its high fuel economy and low emissions, this engine is receiving renewed attention as an automotive engine. Several currently sold diesel vehicles already meet the 1977 emissions standards without any emissions control (Table V-4). As with most of the other stratified-charge engines, the diesel is an inherently low emitter of hydrocarbons and carbon monoxide.

TABLE V-3
Performance of Open-Chamber, Stratified-Charge Engines
Equipped With Oxidation Catalyst

Vehicle	Emissions System	Emissions g/mi			Fuel Economy mpg	Status**
		HC	CO	NO _x		
Jeep, M-151 ¹ 151 CID, MT, 2,750 lb	Texaco TCCS, EGR, turbocharged					R
	a) gasoline	0.33	1.04	0.61	19.7	
	b) JP-4	0.26	1.09	0.50	20.2	
	c) 100-600	0.14	0.72	0.59	21.3	
	d) No. 2 diesel	0.27	1.14	0.60	23.0	
Cricket, ¹ 141 CID, MT, 2,500 lb	Texaco TCCS Retard, EPB,* EGR "Best Economy"	0.36 1.07	1.15 0.84	0.38 1.9	20.2 25.7	R
Ford, ¹ 351 CID, AT, 4,500 lb	PROCO, EGR	> 0.4	< 3.4	0.4	13.3	R
Ford, ² 400 CID, AT, 5,000 lb	PROCO (before the catalyst)	1.7 1.4	12.7 7.1	1.5 1.8	13.8 14.7	R R

*EPB - elevated exhaust back pressure

**R - research

¹ Source: Reference 5.3

² Source: Reference 5.4

TABLE V-4
Mass Emissions and Fuel Economy
From Diesel Engines
(1975 Federal Test Procedure)

Vehicle	No. of Tests	Inertia Weight	Transmission	HC (g/ml)	CO (g/ml)	NO _x (g/ml)	Fuel Economy (mpg)
Mercedes 220D	5	3,500 lb	4 speed auto	0.34	1.42	1.43	23.6
Mercedes 220D (modified)	5	3,500 lb	4 speed auto	0.28	1.08	1.48	24.6
Mercedes 240D	3	3,500 lb	4 speed auto	0.18	1.0	1.5	23.6 ¹
Peugeot 504D	5	3,000 lb	4 speed manual	3.11	3.42	1.07	25.2
Peugeot 504D (modified)	(Manufacturer's Data)	3,000 lb	4 speed manual	0.40-0.60	1.1-1.6	1.3-1.5	--
Datsun-Nissan 220C (as received)	2	3,500 lb	4 speed manual	0.38	1.69	1.72	24.0
Datsun-Nissan 220C (after 4,000 miles)	2	3,500 lb	4 speed manual	0.23	1.34	1.36	28.1
Opel Rekord 2100D	4	3,000 lb	3 speed auto	0.40	1.16	1.34	23.8
Pick-up Truck Retrofit (Nissan Diesel)	3	4,500 lb	4 speed manual	1.70	3.81	1.71	21.4

¹The fuel economy in this case is based on one measurement only.

Source: Reference 5.5

1. Oxides-of-Nitrogen Emissions

The major emissions problem to be solved for the diesel is NO_x . The use of EGR is effective only to about 1 g/mi NO_x , at which point HC and CO emissions are increased. Retarding injection timing also reduces NO_x , but causes an increase in HC and CO. Other methods of reducing NO_x emissions remain in the research stage.

It should be emphasized that there are fundamental reasons which prevent the NO_x control methods that are applied to conventional engines from being effective on diesel engines. Reduction catalysts require a fuel-rich exhaust for their operation and, therefore, cannot be applied to the diesel engine. Larger quantities of exhaust gas recirculation are required for the diesel engine than for the conventional engine. This results in a more difficult problem of hydrocarbon increase and loss of fuel economy for the diesel engine. The different behavior and response of the diesel engine to exhaust-gas recirculation results from its fuel-lean mixture and the nature of the combustion process, which is heterogeneous (diffusion flame) rather than homogeneous (premixed flame).

Because the attainment of a 0.4-g/mi NO_x level for the diesel engine has not been demonstrated, the existence of the 1978 nationwide emissions standard plays a major role in the future of the diesel engine in automotive applications. Either the relaxation of this standard or the development of new diesel NO_x control technologies, or a combination of these, is required if diesel-powered cars are to be sold in the United States after 1978. Since all of these possibilities remain uncertain at the present time, the future of the diesel automobile also is uncertain.

2. Unregulated Emissions

A somewhat similar situation exists with respect to particulates and odor. However, in this instance there are no existing U.S. emissions regulations for these species. The uncertainty about such regulations appears to be causing the automobile industry to delay commitment to a

substantial development program for the automotive diesel. This is probably somewhat overly cautious, as the technological possibility for a significant reduction of diesel particulates and odor is good. Current diesel particulate emissions are about 10 times the suggested standard of 0.1 g/mi. The uncertainty in the future of the diesel engine for automotive use is compounded by the lack of a clear definition of the need for and establishment of regulations for vehicular particulate and odorant emissions.

3. Future Improvements

In addition to resolution of the uncertainties in pollutant emissions, other improvements in the diesel engine are required. The widespread adoption of the diesel engine in automobiles historically has been hampered by real or perceived disadvantages of initial cost, weight, noise, smoke, and odor. Since the diesel cycle does involve a lower volumetric efficiency, higher pressures, and more rapid rates of pressure rise than the conventional Otto cycle engine, the engine has exhibited a weight and noise disadvantage. The need for high-pressure fuel injection also adds to initial cost. Although a lightweight, perhaps turbocharged, diesel engine appears attractive for eventual automotive application, such an engine remains to be developed. As considerations of fuel economy become increasingly important, the competitive position of the diesel will improve.

C. Rotary Engines

Rotary engines, predominantly of the Wankel type, are simply different mechanical configurations of the engine types already discussed. Reciprocating pistons are replaced by one or more rotating drive elements. The resulting engine may be spark- or compression-ignited, although the spark ignition version is by far the most common and the only version which has been placed in production. Most of the reciprocating stratified-charge

concepts also have been applied to rotary engines. In comparison with reciprocating engines, the advantages of the rotary engines lie in their smaller size and weight, smoother operation, and a potentially simpler manufacturing process. The major disadvantages have been associated with seal wear and lower fuel economy. At present, data are lacking which would confirm claims that fuel economy can be made comparable to that of reciprocating engines of equivalent technology.

1. Emissions

In comparison with reciprocating engines, the basic Wankel engine has produced much higher hydrocarbons and lower oxides of nitrogen. As the compression ratio and sealing efficiency have been increased to improve fuel economy, oxides-of-nitrogen emissions have increased. Catalytic reactors have been used with the Wankel engine, but because of the high hydrocarbon levels little catalyst degradation can be tolerated. Emissions-control techniques which are developed for the reciprocating spark-ignition engine should be applicable to the Wankel engine as well. Major efforts are directed to mechanical components and fuel consumption.

Emissions data for several rotary engine configurations are given in Table V-5. The use of a rich thermal reactor (i.e., one that operates with a fuel-rich air/fuel ratio) has been effective for hydrocarbon control and the Federal 1977 Emissions Standard has been met with use of air injection and no catalytic reactor.

Use of a lean-combustion system has provided a 15% to 30% improvement in fuel economy while still meeting the Federal 1977 Emissions Standards with a 3,000-lb vehicle. With the addition of EGR, NO_x emissions have been reduced below 1.0 g/mi, but they are still far above the 0.4 g/mi NO_x level required by the Federal 1978 Emissions Standard. A divided-chamber, stratified-charge rotary engine with a catalytic converter has been reported to have achieved emissions levels for HC, CO and NO_x equivalent to 0.3, 1.7 and 0.4 g/mi, respectively, in a simulated vehicle test. More work on this concept appears to be warranted.

TABLE V-5
Performance of Rotary Engine Systems

Vehicle	Emissions System	Emissions g/mi			Fuel Economy mpg	Status*
		HC	CO	NO _x		
Mazda RX-4 ¹ RE 80 CID, MT, 3,000 lb	Air injection					
	74 Calif. Prod.	2.5	14.0	1.3	11.8	P
	75 Calif. Interim	0.5	6.1	1.7	13.1	P
"	Lean-Combustion System					
	75 Calif. Interim	0.38	4.8	1.7	17.0	PP
		0.18	2.0	1.7	16.4	PP
"	With EGR	0.21	2.4	0.85	15.3	PP
		0.27	2.3	0.74	15.1	PP
	Stratified Charge	0.24	1.8	1.5	17.5	R
80 CID Engine ² tested at 2,750 lb	With EGR	0.22	2.5	0.91	16.8	R
	Divided Chamber	0.3	1.7	0.4	16.0	R
	Strat. charge With catalyst					
GM, 3,500 lb ¹	2 Catalysts	0.30	4.6	1.5	15.0	PP

*P - production; PP - preproduction; R - research

¹Source: Reference 5.6

²Source: Reference 5.7

3. Rotary Diesel

Compound rotary engines (one rotor compresses the intake air for a second rotor) are under development. These diesel-cycle, rotary engines may overcome some of the size, weight, and noise problems of reciprocating diesel engines, but few performance data are available on which to make an assessment of their advantages or potential.

D. Long-Term Alternative Engines

The development of long-term alternative automotive-propulsion systems continues to be focused on the gas turbine, Rankine, and Stirling engines (Table V-6). All of these systems are capable of meeting the 1978 nationwide emissions standards. None of these systems could be placed in mass production before 1980. None of these engines has been shown to be suitable for public use, although gas turbines come closest to having done so. The development of none of the alternative heat engines has yet progressed to a stage where it has been shown to have a cost which would make it suitable for use in conventional automobiles. More descriptive material with references to the outside literature may be found in the Consultant Report on Emissions Control of Engine Systems.^{5.8}

Continuous combustion systems are used with all three of the dominant alternative combustion engines. These systems are inherently lower emitting than the intermittent internal-combustion systems already discussed. The low emissions characteristics of these engines are largely responsible for the recent interest which has been shown in them. All three engines also have the ability to utilize a variety of liquid hydrocarbon fuels.

1. Gas Turbine Engines

The gas turbine has little difficulty in meeting hydrocarbon and carbon monoxide emissions standards. A variable-geometry combustor has

TABLE V-6
Performance of Alternative Engines

Vehicle	Emissions System	Emissions g/mi			Fuel Economy mpg	Status ¹
		HC	CO	NO _x		
GM - CT-225 5,000 lb	GM gas turbine, dual shaft, diesel fuel	0.2	2.7	0.36 ²	-	R
Gas turbine	Zwick combustor	0.26	2.7	0.12 ³	-	
VW Station Wagon 2,750 lb	Carter steam engine	0.40	1.0	0.33	14.9	R
Intermediate size vehicle	Ford/Philips Stirling	0.20	1.2	0.14 ³	14.7	R
Standard size 4,000 lb	Petro Electric Conventional engine electric hybrid Wankel/lead acid	0.45	2.08	0.9-1.1	10.4- 12.4	R
Electric	Electric	0.	0.	0. ⁴		P
Flywheel	Flywheel	0.	0.	0. ⁴		R

¹ P - production; R - research.

² Test cycle used was CVS-C.

³ Emissions measurements based on vehicle simulation.

⁴ Contribution to air pollution depends on location and nature of the primary energy source.

Source: All data is taken from Reference 5.8.

been shown to be effective for meeting the 0.4-g/mi NO_x standard. Another possibility on which little work has been done is the catalytic combustor. It is projected that gas turbine engines available for production in the late 1980's could have fuel consumption measured in the Federal driving cycle lower than that of emissions-controlled, spark-ignition engines. The increased use of ceramic components, especially in turbines, would make the fuel economy advantage even larger. Economical gas turbines are predicted for engines as small as 75 horsepower. Since gas turbines are intrinsically long-life engines, they would give incentive to the use of a long-life vehicle chassis and would thus encourage resource conservation.

Most automotive gas turbine development has been on the regenerated two-shaft engine. More recently, renewed interest in a single-shaft turbine, which requires some form of infinitely variable transmission, has been evident. Some cost studies indicate that the gas turbine could be competitive with the spark-ignition engine in sizes above about 150 horsepower. The cost structure of gas turbine engines, however, remains uncertain at this time. Foreign technology on automotive gas turbines appears to be behind that of the United States companies.

2. Rankine Cycle Engines

The development of Rankine cycle engines for the automotive application has included two types of expanders--reciprocating and turbine--in combination with two types of working fluid--steam and organic. Steam leads to the lightest and most efficient simple engine, with maximum thermal efficiency limited to about 25%. Organic Rankine cycles are generally limited to about 20% at best operating conditions. Developmental Rankine engines demonstrate good emissions characteristics and fuel economy poorer than 1970 model year conventional engine vehicles. Cost remains a major unknown factor for Rankine engines.

3. Stirling Cycle Engines

Continuing development of Stirling engines now includes the demonstration of these engines in automobiles. It has been shown that the engine can be of sufficiently low weight and size and sufficiently rapid response time to be a viable automotive power plant. These engines are extremely quiet, very smooth in operation, low pollutant emitters, have low fuel consumption (close to a diesel engine without emissions controls), and can have long life. Cost and production problems have not been resolved. Current engines should be regarded as experimental and additional development is required. The engine is adaptable to a thermal-energy storage system, should such a concept prove feasible.^{5.8}

4. Electric Vehicles

Based on present technology, it is feasible to manufacture electrically driven personal vehicles for low-performance (short range and low power) urban use. Even when equipped with the best currently available lead-acid storage batteries, these vehicles will have a high initial cost, low energy efficiency, and a high total cost per mile driven.

The duty cycle of delivery vans and urban buses offer an attractive opportunity to introduce electric-powered vehicles with heavy-duty lead-acid storage batteries, even with the limitations of today's technology. Higher-energy and power-density batteries currently under development could make electric vehicles comparable in initial cost and superior in per-vehicle-mile cost than gasoline-engined vehicles. In view of the strong likelihood for a gradual shift toward coal, nuclear, geothermal, and, perhaps, solar primary energy sources, there are strong incentives for the development of advanced storage batteries and electrically propelled vehicles.

5. Flywheel and Hybrid Systems

Interest in the use of flywheels for mechanical energy storage is directed primarily toward urban buses. Flywheel systems have not been shown to be competitive with combustion engines. Heat-engine battery hybrids have been demonstrated which have low emissions and an ability to negotiate the Federal driving cycle. The complexities of these systems have cost implications that have not been resolved. Speculative interest continues for such combustion engines as those based on reciprocating Brayton cycles, with some experimental work being conducted.^{5.8}

VI. COSTS OF EMISSIONS CONTROL

The costs of emissions control contain five major elements:

1. Capital investments for new technologies,
2. Component costs (excluding capital amortization),
3. Increased (or decreased) fuel consumption,
4. Increased (or decreased) maintenance, and
5. Risks associated with failure to meet mandated standards with a significant part of production or with vehicles which are not fully acceptable to the consumer.

During this study, we have developed cost figures for the first four elements, but have not attempted to quantify the fifth. It is clear, however, that if the technological means selected for meeting emissions standards are not achieved on schedule or are not fully acceptable to the consumer, then higher social costs may result than would be revealed by our analysis of the first four elements.

A. Emissions-Control Hardware Costs

Some typical costs for emissions-control hardware components are shown in Table VI-1. The costs listed in this table are estimated manufacturing costs multiplied by a factor ranging from 1.8 for small cars to 2.4 for large cars to cover costs of administration, warranty, dealer mark-up, etc.^{6.1} The component costs in Table VI-1, as well as the more detailed set in the emissions-control cost analyses, were obtained from several sources:

1. Vendor costs to the automobile manufacturers,
2. U.S. manufacturers' cost estimates as supplied in response to our questionnaire,
3. Presentations to CMVE by foreign manufacturers at the May 1974 meeting,

TABLE VI-1

Typical Component Sticker Price
Used in Developing Vehicle Costs

Component	Sticker Price, in Dollars*		
	4 Cyl.	6 Cyl.	8 Cyl.
Air Injection-Pump-Valves-Piping	27	31	33
Fuel-Evaporation Control	8	10	11
Distributor Assembly	7	14	21
PCV Valve	2	2	3
Improved EGR	11	12	14
Most Advanced EGR	18	20	22
Oxidation-Catalyst Pellet Converter	--	--	76
Oxidation-Catalyst Monolith Converter	47	58	--
Reducing-Catalyst Pellet Converter	--	--	82
Reducing-Catalyst Monolith Converter	63	74	--
Oxygen Sensor	4	4	4
Three-Way-Catalyst Pellet Converter	80	92	92
Fuel-Injection Nozzles	25	42	57
Electronic-Emissions Control Unit	50	56	57

*Investment allocation is not included. Blanks in table indicate that costs were not needed for the computer analysis and, therefore, were not developed for this study.

Source: Reference 6,1

4. Prices contained in automotive catalogs, and
5. Computations based on cost per pound of equivalent items to provide a check on the other sources.

Component costs for a specific function depend on engine parameters such as displacement, number of cylinders, and manufacturer. The costs are also not necessarily additive from one year to the next. For example, special controls for spark retard, which were widely used in 1973-1974 vehicles for emissions control, have been eliminated on most catalyst-equipped cars for 1975. Similarly, advanced carburetors and proportional-exhaust-gas-recycle (EGR) systems replace older systems which had already been added or modified for emissions control. It has thus become increasingly difficult for the industry (and for us) to determine just how much of the cost of a given engine system should be attributed to emissions control. Our consultants have, however, attempted to do this by making independent cost estimates for the various components and then developing independent estimates for the various engine configurations.^{6.1}

Typical costs to the customer of emissions-control hardware as estimated by the domestic manufacturers in their responses to a questionnaire prepared by our consultants are shown in Table VI-2, together with estimates by our consultants. The estimates are directly comparable since capital investment costs (which we omit at this level in computer analyses) are included here for both estimates and since our estimates in this case were for hardware configurations similar to those dominantly chosen by the manufacturers. While the estimates are not identical, they are close enough that no significance should be attached to the differences.

We do not include the cost of capital equipment amortization as a fixed element in the cost of emissions-control hardware in our time-dependent cost studies, since it is strongly sensitive to the time rate of buildup of new facilities. Instead, the required facilities are

TABLE VI-2

Conversion Systems Sticker Price Increases Over 1974 Carbureted
Piston Engine Vehicles with Catalyst Subsystems

Engine Size	U.S. 1975				U.S. 1977				U.S. 1978			
	USA Co. Est.	CMVE M/C Panel			USA Co. Est.	CMVE M/C Panel			USA Co. Est.	CMVE M/C Panel		
		Hardware Estimate	Invest- ment	Total		Hardware Estimate	Invest- ment	Total		Hardware Estimate	Invest- ment	Total
4-cyl. 100-150 CID	135	95	12	107	184	137	13	150		250	24	274
		96	18	114		140	19	159		256	33	289
6-cyl. 200 to 260 CID	130	100	12	112	180	152	13	165	287	271	24	295
	165	104	18	122	258	167	19	186	323	293	33	326
8-cyl. 262 to 450 CID	155	133	4	137	220	185	6	191	367	333	19	352
	220	150	7	157	311	213	10	223	498	389	30	419
Scenario Reference		A/C Class 36				A/E Class 50				A/J Class 71		

Notes:

- 1) Two U.S. companies did not submit data for Federal 1978 Emissions Standards.
- 2) 1974 baseline vehicle emission system has PCV/fuel evap./EGR/Improved carburetor/TSC (spark control).
- 3) All costs include tooling, equipment, and facilities investments amortized according to company practices. Two companies included profit and contingencies and two companies did not include profit.
- 4) The two cost figures in each box relate to the upper and lower CID for each engine class.

Source: Reference 6.2

created as required for a given scenario and then the capital costs are determined and allocated to the appropriate technologies.

The level of expenditure for emissions-control-related capital equipment in recent years is summarized in Table VI-3.^{6.3} Since much of the \$654 million was spent for the years 1970-1974, the rate of investment per car is about \$15. However, the investment cost per car will depend on the length of time over which these investments are amortized or averaged.

The computer analyses discussed in Section VII use a three-year amortization period for investment costs but introduce the technology gradually over a ten-to-fifteen-year period. The average investment costs over the period and the highest single-year cost, obtained in this manner for the assumed rates of introduction, range from a low of \$2 to \$3 for the average and highest, respectively, for a 1975 vehicle without catalyst to a high of \$46 and \$79, respectively, for CCS technology introduced at a rate sufficient to satisfy 16% of the automotive engines by 1980. Dual-catalyst and three-way-catalyst systems would have average-to-peak investments of \$24-\$34 and \$9-\$17, respectively, if introduced rapidly enough to supply all domestically produced vehicles for the 1978 model year.^{6.4}

B. Single-Car Cost Analyses

The costs of emissions-control technology have been estimated using simple single-car analyses and also with more sophisticated computer analyses of seven model sizes from mini to luxury. The computer studies reveal investment costs and the interactions of various production decisions which cannot be analyzed by the single-car model. However, for those things that can be studied by simple single-car models the results are qualitatively the same, quantitatively similar, and much easier to present and understand.

TABLE VI-3

Emissions-Related Investments by Domestic Automobile Companies

<u>Component</u>	<u>Model Year Investment</u>	<u>Total Investment</u> ¹
PCV Valve	1968/1970	3,300
Fuel-Evaporation Control	1970/1974	2,300
Transmission-Spark Control	1972	1,700
Air Pump	1973	50,000
	1974	35,000
Air-Injection Controls	1973	5,000
	1974	5,000
Air-Injection Piping	1973	1,100
EGR Valves	1974	3,300
PEGR Valves	1974	4,900
Exhaust Manifolds	1973/1974	12,800
Intake Manifolds	1973/1975	34,500
Coolant Radiator	1972/1973	9,000
Anti-Dieseling Solenoid	1973/1975	7,300
Carburetor	1974	12,000
Aluminum Die Casting	1974	5,300
Electric Choke	1974	3,300
Altitude Compensation	1976	31,500
High Energy Ignition	1975/1976	30,000
Carburetor - Venturi	1974/1975	50,000
Aluminum Die Casting	1974/1975	9,500
Venturi Components	1974/1975	7,000
Carburetor - IFC Air Valve	1974/1975	40,000
Aluminum Die Casting	1974/1975	9,500
IFC Components	1974/1975	4,000
Pellet-Catalytic Converters	1974	16,000
Pellet Can	1974	123,000
Pellets	1974	10,800
Alloy Y Piping	1974	2,800
Monolith Converter	1973/1974	73,000
Monolith Can	1973/1974	11,000
Monolith Substrate	1973/1974	22,000
Monolith Catalysts	1973/1974	8,500
Alloy Y Piping	1973/1974	2,800
Lean-Thermal Reactor	1975/1976	6,800
TOTAL		<u>654,000</u>

¹Total investment includes engineering and launching costs, equipment and tooling costs, and facilities costs in thousands of dollars.

Source: Reference 6.3

Engine systems used to meet past emissions standards and ones which may be used to meet future standards were determined by our staff and technology consultants, while sticker prices (without investment costs) were determined by our consultants on manufacturing.^{6.1} A total sticker price, including investment costs, was then determined based on the average of the peak and average investment costs for the fifteen-year period. The difference between this sticker price and that of an equivalent 1970 intermediate six-cylinder vehicle (equipped with power steering, automatic transmission and air conditioning) is entered in column four of Table VI-4. The sticker price for the 1970 vehicle is \$3,992 when stated in 1974 dollars, as are all costs in this report.

The first column of the table lists engine configurations for meeting the indicated HC/CO/NO_x emissions levels. The abbreviations used are as follows: Modif. is a standard internal-combustion engine modified with EGR, air pump, spark retard, etc.; LBS is a lean-burn system using improved air/fuel mixture preparation; HCAT is a standard engine with HC-CO oxidizing catalyst and other modifications, as necessary; Dual Cat. is a standard engine with both a reducing and an oxidizing catalyst; 3-Way Cat. is a standard engine with combined oxidizing and reducing catalyst, oxygen sensor, and feedback system; CVCC is a prechamber, dual-carburetor stratified-charge engine; and CCS is a direct-fuel-injected, stratified-charge engine. The second column is a computer configuration number that can be used to find more detailed configuration information in the 'Consultant Report to the Committee on Motor Vehicle Emissions on Manufacturability and Costs of Proposed Low-Emission Automotive Engine Systems.'^{6.5}

The estimated miles per gallon for each vehicle configuration with equivalent performance is shown in the third column and is based on estimates by our staff and consultants.^{6.6} The configuration numbers shown in parentheses are for vehicles originally configured for a different standard. The use of such a vehicle for a more or less

TABLE VI-4

Comparative Emission Control Cost Data for Various Systems and
Emission Levels Based on Intermediate Six-Cylinder Vehicles*

Emission Level and Vehicle System	Config. No.	MPG	Increase in Lifetime Cost (\$)				Discounted Life Total** (\$)
			Sticker Price	Fuel	Maint.	Total	
3.9/33/6 Base	25	13.2	0	0	0	0	0
3.0/28/3.1 Modif.	11	12.1	51	296	325	672	557
1.5/15/3.1 Modif.	32	12.4	78	210	325	613	512
LBS	--	13.9	110	-164	200	146	134
HCAI	39	13.5	123	76	100	298	265
0.9/9.0/2.0 Modif.	(32+)	12.0	87	325	325	737	617
LBS	--	13.6	110	- 96	200	214	190
HCAI	46	13.1	167	178	113	458	405
Dual Cat.	(221)	13.5	249	75	75	399	371
3-Way Cat.	(137)	13.9	326	- 11	12	327	326
CVCC	(88)	13.3	210	- 25	325	510	412
CCS	(214)	15.4	230	-661	12	-419	-310
Diesel	(193)	16.5	149	-713	- 75	-639	-503
0.4/3.4/2.0 LBS	--	13.3	120	- 25	200	295	259
HCAI	53	13.1	193	177	113	483	431
Dual Cat.	(221)	13.1	249	177	75	501	455
3-Way Cat.	(137)	13.6	326	51	12	389	378
CVCC	(88)	13.1	210	24	325	559	490
CCS	(214)	15.4	230	-661	12	-419	-310
Diesel	(193)	16.5	149	-713	- 75	-639	-503
0.9/9.0/1.0 Modif.	(32+)	10.8	87	724	325	1136	948
HCAI	(46)	11.8	167	555	112	834	718
Dual Cat.	(221)	13.3	249	125	75	449	413
3-Way Cat.	(137)	13.7	326	27	12	365	356
CVCC	(228)	13.2	209	- 1	200	408	352
CCS	(158)	14.8	273	-556	37	-246	-158
Diesel	(200)	15.1	167	-477	- 25	-335	-250
0.4/3.4/1.0 Dual Cat.	221	12.9	249	230	75	554	500
3-Way Cat.	137	13.5	326	75	12	413	398
CVCC	228	12.2	209	267	200	676	575
CCS	158	14.5	273	-499	38	-188	-111
Diesel	200	15.0	167	-458	- 25	-316	-234
0.4/3.4/0.4 Dual Cat.	74	12.3	331	401	75	807	724
3-Way Cat.	144	13.2	377	151	38	566	531
CVCC	95	10.6	215	799	225	1239	1057
CCS	(158)	13.3	273	-251	38	60	94

*See text for discussion of all entries in this table.

**See Table VI-6 for uncertainties in these numbers.

stringent standard means that no change other than retuning (with a resulting change in emissions and fuel economy) is required to meet the different emissions levels. Lifetime fuel costs are estimated assuming 100,000 miles and a price per gallon of 43¢ (excluding the tax, which is typically 12¢) for leaded gasoline, 45¢ for unleaded, 40¢ for CCS fuel, and 42¢ for diesel fuel. (The basis for these fuel costs is given in the Consultant Report.^{6,7}) The cost analysis performed on the various systems assumes that standard engines without catalysts and the LBS and CVCC engines will use the leaded fuel, while all systems with catalysts (HCAT, Dual Cat. and 3-Way Cat.) will use unleaded fuel. Diesels, of course, use diesel fuel and the lowest cost fuel is used by the CCS engines. The cost advantage of using the lower-cost leaded fuel is found to be approximately offset by the higher cost of maintenance resulting from more frequent engine tune-ups, spark-plug replacement, EGR valve cleaning, etc.

There is a relatively large difference of \$325 assumed between the lifetime cost of maintaining the emissions-control-related items on a 1970 and a 1974 vehicle. This is \$26 per 10,000 miles at low mileage and somewhat more as the vehicle ages. Of this, \$10 to \$15 per 10,000 miles is associated with maintenance of additional emissions-control-related equipment such as EGR. The remainder results primarily from more frequent engine adjustments and spark-plug replacements, which are specified at 12,000 miles for most 1973-1974 vehicles but were made "as needed" for 1970 vehicles.^{6,8} There is, therefore, substantial uncertainty in this maintenance cost difference estimate. Maintenance cost estimates for vehicles meeting more stringent standards than the 1974 Federal Emissions Standards were based on considerations of differences in engine complexity and the use of leaded or unleaded fuels, using 1974 vehicles as a base. Lifetime maintenance has been obtained by multiplying the early 10,000-mile maintenance estimates by 12.5 (instead of 10 for the expected life) to account for the anticipated higher maintenance per mile in later years.

The differences between lifetime costs for fuel and maintenance and the differences in total lifetime costs are shown in columns five, six and seven, respectively. Finally, column eight displays the incremental lifetime cost over 1970 vehicles, in which the fuel and maintenance costs have been discounted at 4% per year over the ten-year life of the vehicle.

The last column of Table VI-4 is then summarized in Table VI-5 in order to display discounted lifetime costs for the different technologies designed to meet various emissions standards. An "X" in this table indicates that the technology was not expected to be able to meet the standard.

The data presented in Table VI-4 and VI-5 lead to a number of observations regarding the lifetime costs of emissions-controlled, six-cylinder, intermediate-sized vehicles:

1. The lifetime cost increase resulting from the poorer fuel economy and higher maintenance costs of 1973-1974 vehicles is 10 times larger than that due to the increased sticker price.
2. The average catalyst-equipped car meeting the 1975 Federal Emissions Standards will get about 2% better fuel economy than an equivalent 1970 vehicle. If we had used the same price for lead-free gasoline as leaded gasoline, the increased lifetime operating cost of this vehicle over equivalent 1970 vehicles would drop from \$265 to \$140.
3. The average catalyst-equipped car meeting the 1975 California Emissions Standard will have nearly the same fuel economy as equivalent 1970 vehicles. The increased operating cost over 1970 vehicles is about \$400 compared to \$265 for federal 1975 vehicles.

TABLE VI-5

Summary of Lifetime Cost Differences for Vehicles
Manufactured in 1978 to Meet Hypothesized Standards

Hypothesized Standards HC/CO/NO _x	Engine Systems							
	Modif.	LBS	HCAT	Dual	3-Way Cat.	CVCC	CCS	Diesel
1.5/15/3.1	512	134	265	371	326	449*	-310	-503
0.9/9.0/2.0	617	190	405	371	326	449*	-310	-503
0.4/3.4/2.0	X	259	431	455	378	490*	-310	-503
0.9/9.0/1.0	948	X	718	413	356	350	-158	-250
0.4/3.4/1.0	X	X	X	500	398	575	-111	-234
0.4/3.4/0.4	X	X	X	724	531	1057	94	X

Notes:

- 1) All entries in this table are based on the last column of Table VI-4.
- 2) Emissions are stated in grams per mile.
- 3) Cost differences are given in 1974 dollars and include changes in sticker price, fuel usage and maintenance. The maintenance and fuel costs have been discounted at a 4% rate over the life of the vehicle.
- 4) Comparisons are for six-cylinder, intermediate vehicles of equivalent performance as measured against an equivalent 1970 vehicle.
- 5) To provide equivalent performance, the diesel-powered vehicle has a 10% larger CID engine and about 200 pounds more weight than the other vehicles.
- 6) Fuel costs without taxes are assumed to be 43c/gal for leaded gasoline for the Modif. and CVCC systems; 45c/gal for unleaded gasoline for the HCAT, Dual and 3-way Cat. systems; 40c/gal for CCS fuel; and 42c/gal for diesel fuel.

* If experience with CVCC engines now in use should indicate that the cost of maintaining the dual-carburetor system is no higher than that of a conventional carburetor system, then the lifetime costs would be lower than indicated here (and in Table VI-4) by \$100 to \$150.

4. Large savings in lifetime costs, especially in fuel consumption, appear to be possible with CCS and diesel technology if NO_x standards are not reduced below 1.5 to 1.0 g/mi.
5. Much of the projected costs of meeting NO_x standards below 2.0 g/mi, and especially below 1.0 g/mi, result from anticipated poorer fuel economy resulting from EGR. As the technology is further developed, the higher cost of meeting the more stringent standards is expected to be reduced substantially.

The precision indicated in Tables VI-4 and VI-5 is far greater than warranted by the many uncertainties in the basic data, but has been preserved to aid the reader in following the analysis. Consistent errors as large as \$100 may result from our assumed differences in the prices of various fuels. More nearly random errors may result from a variety of uncertainties in hardware costs, fuel economy and maintenance. A \$10-per-year error in fuel economy or maintenance costs will produce an error of about \$80 in total lifetime costs after discounting at 4% per year. Our analysis (completed before all 1975 cars were certified) shows federal 1975 intermediate six-cylinder vehicles achieving about a 3% better fuel economy than equivalent 1975 California vehicles. Newer data suggest that 5% may be a better estimate, even for the more sophisticated configurations we have used for California than for Federal 1975 Standards. This 2% uncertainty in miles per gallon leads to a \$55 uncertainty in discounted lifetime operating costs. Furthermore, the uncertainty in maintenance costs for the various configurations is probably even larger.

The projected increased costs over 1970 vehicles of meeting various standards which were hypothesized for 1978 are shown in Table VI-6 together with the uncertainty of the projections. Possible consistent errors due to fuel cost uncertainties are not included. The uncertainties shown in the table increase more rapidly than the

TABLE VI-6

Cost of Meeting Various Emissions Standards in 1978
with Catalyst-Equipped Vehicles

Hypothesized Standards HC/CO/NO _x	Lifetime Cost per Car in 1974 Dollars
1.5/15/3.1 g/mi	\$250 ± 100
0.9/9.0/2.0 g/mi	\$350 ± 150
0.4/3.4/2.0 g/mi	\$400 ± 200
0.9/9.0/1.0 g/mi	\$400 ± 200
0.4/3.4/1.0 g/mi	\$450 ± 250
0.4/3.4/0.4 g/mi	\$600 ± 350

Notes:

- 1) Comparison is based on six-cylinder intermediate vehicles of equivalent performance using a 1970 vehicle as the base.
- 2) Costs are stated in 1974 dollars and include emissions-control-related changes in sticker price, maintenance costs and fuel usage. Maintenance and fuel costs are discounted at 4% over the life of the vehicle.
- 3) Only the HCAT, Dual-Cat. and 3-Way-Cat. systems listed in Table VI-5 have been used as a basis for these estimates since a modified conventional engine without catalysts is not economical and because domestically produced LBS, CVCC, CCS and diesel technology could not be significant factors in the market in 1978.
- 4) The indicated uncertainties represent our judgment of the collective effect of uncertainties in estimating sticker price, fuel consumption and maintenance costs of the various systems as they might actually exist in 1978. This is discussed more fully in the text.

actual projected costs because they are strongly dependent on the rate at which technology evolves for reduction catalysts. For example, if technology evolved sufficiently to eliminate EGR entirely in dual-catalyst and 3-way-catalyst systems for the 1978 Federal Emissions Standards, then fuel economies equivalent to those of catalyst-equipped cars meeting the Federal 1977 Emissions Standards might be achieved. This alone would reduce the discounted lifetime costs for both systems to about \$500.

The average cost estimate given in Table VI-6 is based only on conventional engines with catalysts because conventional noncatalyst systems are not cost effective and because LBS, CVCC, CCS and diesel technology could not reach as much as 10% of domestic production by 1978.

C. The Consumers' View of Costs

Some of the data and analysis developed by CMVE consultants have been used for an earlier study by the National Academy of Sciences. Volume 4 of that study, The Costs and Benefits of Automobile Emission Control, considers, among other things in their Table 2-9, the cost of emissions control as viewed by the automobile buyer.^{6.9} Entries from that table are reproduced in Table VI-7 of this report with three additional columns that are designed to relate that report more directly to this one.

The buyer is influenced by the total cost of operating a vehicle, whether or not part of the cost is a tax on gasoline which is returned to society and, therefore, not a cost to society. Studies of consumer buying decisions suggest that consumers may discount the value of money in the future at a much higher rate than is economically justifiable for society as a whole. That study suggested a 15% discount rate as an upper limit to test the effect of higher discounting in contrast to the 4% rate used in both studies for social costs. The

TABLE VI-7
Single-Car Costs of Standards on Schedule
(Lifetime Cost Increase over 1970 Intermediate Six-Cylinder Vehicles in 1974 Dollars)

Standard	Config. No.	List Price	Life Maint.	Life Fuel			Life Total			Present Value					
				Tax		Ex. Tax	Tax		Ex. Tax	Without Investment		With Investment		Tax ²	Ex. Tax ³
Federal 1970	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Federal 1973	11	49	325	379	296	753	670	432	555	434	557	434	557	434	557
Federal 1975	39	109	100 ⁴	56 ⁶	76 ⁶	265 ⁴	285 ⁴	203 ⁴	252 ⁴	216 ⁴	265 ⁴	216 ⁴	265 ⁴	216 ⁴	265 ⁴
Cal. 1975	46	150	113 ⁴	184	178	447 ⁴	440 ⁴	330 ⁴	388 ⁴	347 ⁴	405 ⁵	347 ⁴	405 ⁵	347 ⁴	405 ⁵
Federal 1977	53	176	113 ⁴	184	178	473 ⁴	466 ⁴	361 ⁴	414 ⁴	378 ⁴	431 ⁴	378 ⁴	431 ⁴	378 ⁴	431 ⁴
Federal 1978	74	302	75 ⁵	467	401	844 ⁵	778 ⁵	649 ⁵	695 ⁵	678 ⁵	724 ⁵	678 ⁵	724 ⁵	678 ⁵	724 ⁵

¹ See Consultant Report to the Committee on Motor Vehicle Emissions on Manufacturability and Costs of Proposed Low-Emissions Automotive Systems, October 1974, for description of each configuration, 6.10.
² Lifetime maintenance and fuel costs discounted at 15%.
³ Lifetime maintenance and fuel costs discounted at 4%. Note that this lower rate of discounting causes the lifetime costs to be higher in spite of the fact that the gasoline tax is not included.
⁴ Catalyst replacement at 50,000 miles would add \$30 to \$120.
⁵ Catalyst replacement at 30,000 miles would add \$50 to \$300 depending on whether the active material only is replaced or the whole unit.
⁶ The higher cost of the fuel, when calculated without tax, results from the lower fuel consumption of the 1975 technology compared to the 1970 technology. The assumed higher cost of unleaded fuel causes there to be a net cost rather than net savings in spite of this lesser use.

fourth column from the right in Table VI-7 (which is also the last column of Table 2-9 of the earlier report) shows the cost of selected emissions-control technologies as viewed by a consumer who includes gasoline taxes in his costs and may discount his money at a 15% rate. The third column from the right displays the costs with the gasoline tax omitted and a 4% discount rate, which is more appropriate for estimating social costs.

The last two columns repeat the first two columns with, however, the investment costs included. These costs were intentionally omitted from all single-car analyses of the previous study because they are derivable by us only through a computer analysis and because their magnitudes are dependent on the rate at which new technology is introduced. (In Table VI-4, investment costs are included in the sticker price.) The numbers in the last column of Table VI-7 are a subset of the numbers in the last column of Table VI-4.

The social cost increase over uncontrolled 1970 technology as determined by us using the 4% discount rate, excluding the 12¢ per gallon tax on fuel and including the investment costs, is 12% to 30% higher than the hypothesized view of a consumer who might include taxes and discount his money at a rate as high as 15%. Considering the uncertainties in the cost estimates on which these analyses are based, this difference is insignificant.

D. Impact of New Technology

The impact of new technology is clearly revealed in Tables VI-4 and VI-5. Oxidation catalysts (HCAT) introduced on the 1975 models are expected to restore fuel economy to 1970 levels and to reduce the increase in lifetime costs to half the increase observed in 1973 vehicles. The operating costs of this system rise rapidly as the NO_x standard is lowered. However, the dual-catalyst, 3-way catalyst, and the CVCC systems are expected to be able to provide good fuel economy down

to the Federal 1977 Emissions Standards and perhaps to a 1.0 NO_x level. The lower maintenance costs for the CVCC at the lower NO_x levels results from an assumed improvement in the carburetion system proposed by Honda. Presumably this could as well be used for higher NO_x levels and thus represents a potential cost saving for all standards.

The rapid rise in cost below 1.0 NO_x results primarily from poorer projected fuel economy associated with heavy use of EGR. As the catalyst technology develops, it is possible that this difficulty will be overcome so that fuel use at the 0.4 g/mi NO_x level will be little higher than in the 1.0 to 2.0 g/mi range. However, we do not expect this much progress in time for the 1978 model year. We have assumed that no catalyst change will be required in 50,000 miles. If this much technological progress is not achieved by 1978, then the lifetime cost would increase by at least \$50 and perhaps by \$300 or more.

The diesel and CCS systems are clear economy winners for all projected HC and CO standards and for NO_x standards at least as low as 1.5 g/mi.

The time at which alternative technologies can first be manufactured domestically is governed by the rate at which the remaining technological problems are solved and the time required to tool for mass production. CMVE estimates of probable introduction times for various advanced technologies are shown in Table VII-1. Conversion of a substantial part of the domestic production to any one of these new engines would, however, take many more years because of limited tooling resources as is discussed more fully in Section VII.

These long production lead times clearly indicate that emissions standards imposed before 1985, at least, will have to be satisfied by modifications of existing engines. The dual-catalyst and three-way catalyst systems under development could be manufactured in time for 1978 models, although substantial risks would be incurred since major investments in production tooling would have to be made before the performance of the system is fully known.

E. Impact of Delaying or Modifying Standards

Figure VI-1, based on calculations by Dewees,^{6.11} shows what is expected to happen to average emissions per operating automobile as a function of time for various final standards. The effect of these emissions rates on air quality cannot be assessed without detailed analysis of miles traveled in a given area, weather conditions, topography, etc. Furthermore, high average emissions levels may be very serious in a highly congested region and of no importance at all in a more remote area.

Curve A of Figure VI-1 assumes no changes were made after the Federal 1970 Emissions Standards, Curve B assumes no changes are made after the Federal 1975 Emissions Standards, and Curve C is based on the standards of the present law. Curves D, E, F and G represent hypothesized alternative standards as described in the figure caption. All curves are computed assuming an 11% sales drop in 1974 and then a 3.5% per year growth thereafter and that the distance traveled by cars decreases from 16,000 miles the first year to 7,000 miles in the tenth.^{6.12} Cars are assumed to be better than the standard when new, to just meet the standard at 50,000 miles, and to continue to deteriorate to the end of their life.

The cost of meeting the hypothesized emissions standards over the length of time for which the total emissions have been plotted is difficult to assess because of the uncertainty in the rate of technological progress. Such analyses may, in fact, be quite misleading. However, if the analysis is limited to the expected lifetime costs per car produced in 1978 to meet various hypothesized standards, then our uncertainty is greatly reduced. Our estimates (with uncertainties) are shown in Table VI-6.

The effects on average emissions per operating vehicle of three different time tables for reaching the 0.4 g/mi NO_x standard are illustrated by curves I, J, K and L of Figure VI-2.^{6.11x} Curve I represents

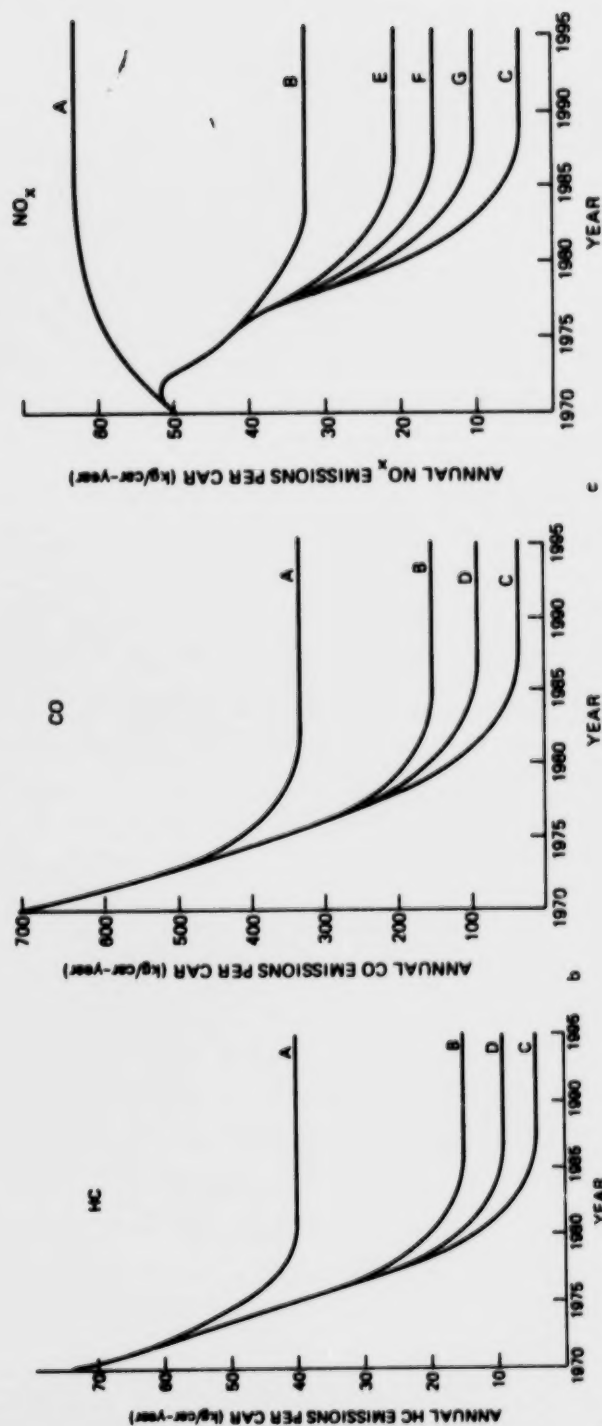


FIGURE VI-1 Annual Emissions per Car for Various Assumed Timing and Ultimate Emissions Standards.

- Curves A: The Federal 1970 Emissions Standard continued unchanged to 1985.
 Curves B: The Federal 1975 Emissions Standard continued unchanged to 1985.
 Curves C: Legislated standards implemented on schedule.
 Curves D: A standard of 0.9 g/mi for HC and 9.0 g/mi for CO adopted in 1977 and then not changed.
 Curve E: The 2.0 NO_x standard is adopted in 1977 and then not changed.
 Curve F: A 1.5 g/mi NO_x standard is adopted in 1978 instead of 0.4 g/mi.
 Curve G: A 1.0 g/mi NO_x standard is adopted in 1978 instead of 0.4 g/mi.

Source: Reference 6.11

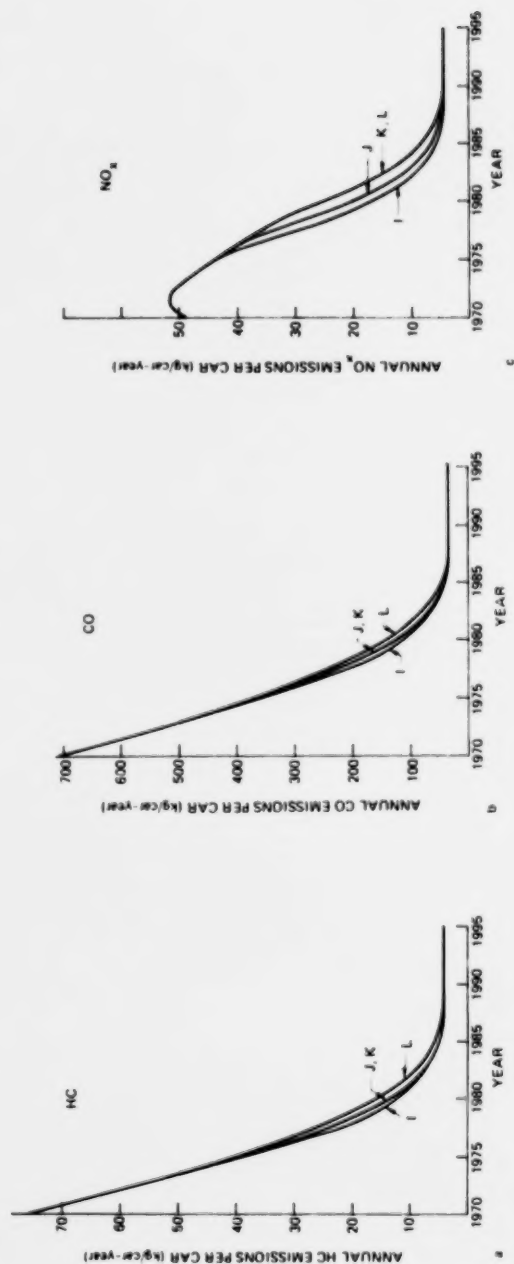


FIGURE VI-2 Annual Emissions per Car for Various Assumed Timing for Emissions Standards.

Curves I: Standards as mandated prior to June 22, 1974.

Curves J: Standards following the signing of Public Law 93-319. This law delays from 1976 to 1977 the imposition of the 0.41/3.4 g/mi standards for HC/CO and from 1977 to 1978 the imposition of the 0.4 g/mi NO_x standard.

Curves K: The 0.4 g/mi NO_x standard is further delayed to 1980.

Curves L: Federal Standards for HC/CO/ NO_x of 0.9/9.0/2.0 g/mi imposed in 1977 followed by 0.41/3.4/0.4 g/mi in 1980.

Source: Reference 6.11

the projected standards before passage of Public Law 93-319 in June 1974, curve J is the present law, curve K is the same as J through 1977 but then delays the 0.4 g/mi NO_x standard to 1980, and curve L assumes the present California Standard is adopted nationally in 1977 and that the Federal 1978 Emissions Standard is delayed to 1980.

A computer model was used to analyze the cost of cases I, J and K. Using the same technologies to meet schedules I and J resulted in a saving of \$4 billion (out of \$72 billion) over the fifteen-year period from 1970 to 1985. This saving is about equally divided between gasoline use and list price. When case K was run there was an additional savings of \$7 billion. About 75% of this savings resulted from changes in fuel consumption.^{6.13,6.14}

The rate of reduction of HC and CO emissions is little altered by delaying from I to J, K or L, as can be seen in Figure VI-2a and b. Delaying the 0.4 g/mi NO_x standard from 1978 (present law, curve J) to 1980 (curves K and L) results in a 50% instead of a 70% reduction in NO_x by 1980 and an 82% instead of an 88% reduction by 1985 using NO_x emissions in 1970 as the base. The associated cost saving over the 15-year period is about 15%.

F. A Two-Standard Strategy

It has frequently been suggested that stringent pollution controls should be adopted only in geographical regions with severe air-quality problems. If we assume, for example, that one third of the fleet followed the present legislated standards and two thirds remained at the Federal 1975 Emissions Standards, then the increased lifetime costs for 1978 model cars over uncontrolled 1970 cars would be \$250 for two thirds of the cars and about \$600 for one third (see Table VI-6). Using this hypothesized two-standard strategy, as opposed to the planned single standard, for the estimated ten million domestically produced cars in 1978, a total lifetime savings of about \$2.3 billion would result. This

saving could be nearly doubled if the standard for two thirds of the fleet were eased enough to eliminate the need for catalysts and fuel-economy-penalizing devices such as EGR and spark retard.

This rough single-car analysis is supported by a more detailed computer calculation in which total costs from 1970 to 1985 are calculated for all vehicle classes. The total savings of a two-standard strategy from 1975 to 1985 are about \$23 billion and the estimated savings in 1985 are \$3 billion on the assumption that no technological progress occurs after 1978.^{6.15,6.16}

The assumption of no technological progress beyond 1978 is, however, not realistic and causes the cost of emissions control to 1985 to be overstated. For example, if reduction-catalyst technology were to improve in time so that little, if any, EGR were required to meet the 0.4 g/mi NO_x standard, then the fuel economy at a standard of 0.4/3.4/0.4 g/mi should be little different than at a standard of 0.4/3.4/2.0 g/mi. This alone would reduce the estimated lifetime cost per car from \$724 to \$540 for the dual-catalyst and from \$531 to \$448 for the three-way-catalyst system. The average lifetime cost of \$500 per car meeting the Federal 1978 Emissions Standards after this hypothesized technological development is about \$100 per car less than the estimated cost for 1978. The savings from the hypothesized two-standard strategy would then be reduced from \$350 per car to \$250 and the national saving would drop from \$2.3 billion to \$1.7 billion.

G. Cost Savings of Smaller Cars

It has also been suggested that a shift to smaller cars would reduce the cost of emissions control. Clearly the total cost of motoring would be less with smaller cars; however, the problem is to separate the reduction in control costs from the reduction in total costs. This can be addressed in a crude way with a single-car analysis as illustrated in Table VI-8.

TABLE VI-8

Emissions Control Lifetime Cost Reduction Resulting
from a Shift in Vehicle Size

Vehicle Size	Subcompact	Intermediate Six	Standard
Inertia Weight	2,500	3,500	4,300
Engine CID	150	250	400
Federal 1970 Emissions Standard			
Vehicle Class ¹	(23)	(25)	(27)
List Price ²	2,400	3,992	5,305
Fuel ³	1,940	2,704	3,336
Maintenance ⁵	<u>360</u>	<u>444</u>	<u>520</u>
Total	4,700	7,140	9,161
Federal 1978 Emissions Standard			
Vehicle Class ¹	(72)	(74)	(76)
List Price ²	2,693	4,323	5,705
Fuel ⁴	2,031	3,037	3,890
Maintenance ⁵	<u>480</u>	<u>504</u>	<u>720</u>
Total	5,204	7,864	10,315
Cost Increase	504	724	1,154
Pollution control lifetime costs differences: in dollars as percent of total			
Subcompact versus Intermediate Six		\$220	8%
Intermediate Six versus Standard		\$430	17%
Subcompact versus Standard		\$650	13%

¹Classes 24 and 25 are conventional, unmodified engines while classes 73 and 74 are dual-catalyst systems.

²List price includes emissions control investment cost.

³Leaded fuel at 43¢/gal, tax excluded, cost discounted at 4% per year.

⁴Unleaded fuel at 45¢/gal, tax excluded, cost discounted at 4% per year.

⁵Cost of maintaining emissions control items only, over life of vehicle and discounted at 4% per year.

Source for fuel use: Reference 6.15

Source for sticker price: Reference 6.1

Source for maintenance: Reference 6.8

Three different vehicle sizes have been considered: a subcompact, an intermediate six and a standard. Lifetime operational costs are calculated for sticker price, fuel costs and cost of maintaining emissions-related items only. Thus, the total costs of ownership are actually higher than the "totals" shown in Table VI-8 and would show further savings for the small cars.

The lifetime cost increases associated with emissions control for the three vehicle sizes are \$504, \$724 and \$1,154, respectively. The differences in lifetime pollution-control costs between the various sizes are given in dollars and as a percentage of the "total" cost of operating the vehicle. This analysis shows the control cost to rise as a percentage of the "total" cost as vehicle size increases. This occurs primarily because of the much greater difficulty of controlling NO_x with larger cars and the associated greater fuel economy penalty.

VII. DEVELOPMENT, TOOLING AND MANUFACTURING CONSTRAINTS FOR U.S. PRODUCTION

The technological attributes, such as fuel economy and operating costs, of various emissions-control systems for light-duty motor vehicles have been treated in previous sections. This section discusses the time frame in which various systems can be implemented in terms of the three primary constraints: development time, tooling time required to implement the first mass-production line, and resources available to convert a significant fraction of the U.S. production to the new system.

A. Development Times

The development status of emissions-controlled engine systems not presently being manufactured in the United States has been discussed in Sections IV and V. Based on this information, a minimum time has been estimated for the completion of development work which is judged to be required before production tooling could be initiated. Those estimates are given in Table VII-1, together with estimates of the minimum tooling time required to have one mass-production line in operation. The development time estimated for dual-catalyst and three-way-catalyst systems is based on the rapid rate of progress toward achieving greater durability in these systems tempered by the fact that 50,000-mile durability has not yet been demonstrated by any of these systems.

B. Tooling Lead Times

The tooling lead times for the various technologies or the times from initiation of the tooling effort to production, are given in Table VII-1. This time is estimated to be 18 months for the dual-catalyst system, 36 months for the fuel-injected, prechamber, stratified-charge engine, and 30 months for all other systems.

The much shorter time for the dual-catalyst system results from the fact that no major modifications of the engine itself are required. Facilities must be constructed to fabricate the dual-catalyst housing

TABLE VII-1

Timetable for the Fastest Transfer of Alternative-
Engine Technology from Development to Mass
Production in the United States

<u>Engine Technology</u>	<u>Phase</u>	<u>Start</u>
1. Dual catalyst	Development	Present
	Tooling	Jan. 76
	Production	July 77
2. EFI with three-way catalyst	Development	Pre-74
	Tooling	July 74
	Production	Jan. 77
3. CVCC	Development	Pre-74
	Tooling	Jan. 75
	Production	July 77
4. Fuel-injected, prechamber, stratified-charge	Development	July 74
	Tooling	July 75
	Production	July 78
5. CCS	Development	Pre-74
	Tooling	July 76
	Production	Jan. 79
6. Diesel of imported design	Development	Completed
	Tooling	Jan. 75
	Production	July 77
7. Diesel of U.S. design	Development	July 74
	Tooling	Jan. 77
	Production	July 79

Source: Reference 7.1

assuming both catalysts (plus oxygen getter for certain systems) are housed in one metal unit or to fabricate separate housings if they are not in one unit. Facilities for manufacturing pellet, monolith, or base-metal units must also be provided. None of these are particularly sophisticated components, so that a minimum amount of time would be required. The 18-month estimate for these dual-catalyst facilities is based partly on the industry's recent experience in developing oxidizing catalyst facilities. A number of other automotive tooling times are quite similar:^{7.2}

1. Vehicle assembly lines, including chassis assembly lines, require about 20 months;
2. Body assembly lines require about 20 months to design and build the automatic press welders, body bucks, work-handling conveyors, etc.;
3. Body press and forming lines require about 15 to 18 months;
4. Engine assembly lines require about 20 months; and,
5. Component assembly lines require 12 to 16 months to design and build.

The multi-station metal-cutting transfer lines used to manufacture cylinder blocks, cylinder heads, manifolds, transmission cases, rear axle housings, carburetor bodies, etc., require two to three years to design, install and debug.^{7.2} Such lines may be several hundred feet in length with numerous metal-cutting-tool operating stations and range in cost from \$2 million to \$15 million. Typical annual production of such a line is 300,000 units on a two-shift, five-day-per-week schedule, and almost twice that on three shifts and six days per week. All of the emissions-controlled engine systems in Table VII-1, except the dual-catalyst system, would require some new lines of this latter class or major modifications of existing lines. This fact is reflected in the estimated lead times shown in the table.

In developing the data for Table VII-1, it was assumed that one of the major U.S. automobile manufacturers made a major commitment to

produce the engine specified. If two or more technologies were to be brought in together, the engine system given priority by the manufacturer would have the schedule indicated, while lower priority systems would be delayed. It should also be mentioned that, to our knowledge, no U.S. manufacturer is currently committed to bring in any of the specified systems on the schedule indicated.

C. Constraints on Rapid Conversion to Alternative Technologies

If the U.S. automotive industry were to bring in a new engine technology on the schedule indicated in Table VII-1, it would not be possible to change over to that technology completely in the first year or so of production. The reason is that several constraints or limitations exist on the rate of production expansion of a new engine technology which result from the size of the industry and the complex internal balance of the factors of production. Some interacting production objectives which the industry seeks to balance are as follows:^{7.1}

1. To keep the production volume in mass-production lines balanced. Parts costs are lowest when lines are run near their optimum volume.
2. To keep individual profit centers profitable. The division of the major companies into identifiable profit units has been a major fiscal control strategy, which may occasionally impede the rapid introduction of new technology.
3. To limit warranty costs. Warranty costs per car, which are in the range of \$5 for the engine and drive-train system, are rapidly increased with even small changes in engine systems reliability because of the large production rates.
4. To use proven, experienced manufacturing managers. Senior manufacturing managers typically have over 20 years experience in the industry. If the pace of new product and facilities introduction is accelerated, this pool of experienced managers

is extremely overloaded, and only a few acceptable managers can be brought in from other industries.

5. To minimize disruption of the vast network of vendors and suppliers. The automotive industry has traditionally used a large number of vendors for the production of small parts and assemblies for which transportation and materials handling costs are small. These parts are made by numerous vendors, who, in turn, have a network of suppliers. Large-scale and rapid product changes severely dislocate this network, raise costs, and increase scrap rates.
6. To invest conservatively in facilities for new product designs. In recent years, the U.S. automobile industry has allocated 300 to 400 million dollars, or \$30 to \$40 per car, for new production facilities to make products of new design. This investment is in a sense speculative compared to that made to replace plant and equipment for continuing, proven parts and subsystems. From 1970 to 1974, \$130 million, or \$15 per car, of this allocation has been devoted to new emissions-control designs. (See Table VII-2.)
7. To balance the load on the machine-tool industry. In 1974, nine companies supplied 96% of the metal cutting transfer lines used by the U.S. automobile industry. Since this capability is small, highly skilled, and difficult to expand, it is important that the industry do what it can to balance their requirements on this sector.

While the first six factors must be kept in balance and this is, no doubt, a continuing and very real problem for management, they do not appear to provide a constraint beyond that in many other industries. A very real constraint to rapid conversion to a new engine technology is, however, provided by limitations in the tooling industry.

The survey of this industry by some of our consultants indicates that it is a very limited resource which would be difficult to expand

TABLE VII-2

Emissions-Related Investment by the U.S.
Automotive Industry, 1970-1974

1. Total Emissions-Related Investment 1970-1974		\$650,700,000*
2. Average Investment Per Year 1970-1974 (One fifth of Item 1)		\$130,140,000
3. Total Car Production by U.S. Builders (including Canadian production) for the U.S. Market. (From Manufactur- ability and Costs Consultant Report)	1970 1971 1972 1973 1974 TOTAL	7,115,000 cars 8,676,000 9,321,000 9,669,000 8,625,000 (est.) 43,406,000 cars
4. Average Emissions-Related Investment Per Car 1970-1974 (Item 1 divided by Item 3).		\$15.00 per car

*This number can be derived from Table VI-3 by subtracting the \$3,300,000 spent in 1968/70 for PCV valve tooling.

rapidly.^{7.2} Some results of that survey are shown in Table VII-3. It can be seen that the automotive industry in 1974 used 92/260 or 35% of the capacity of that sector of the tooling industry which can be applied to automotive manufacturing.

D. Technology Conversion Studies

In order to determine the investment costs and impact on the tooling industry of different combinations of emissions standards and engine technologies, a series of hypothetical time-phased production plans, or scenarios, were studied.^{7.3} Each scenario began in 1970 with the uncontrolled baseline vehicle (class 22) and was run to 1985. These scenarios are described in Table VII-4 and their impact on capital investments is shown in Table VII-5.

The first four columns in Table VII-4 give, respectively, a scenario descriptor, the final emissions standards selected for the given scenario, and a numerical descriptor followed by a brief verbal description of each vehicle class assumed to be in production toward the end of the scenario. These vehicle classes are more fully described in a Consultant Report.^{7.4} The last three columns list the year in which the vehicle system was first introduced and the percent of the domestic production it represented in 1980 and in 1983.

In Table VII-5, the first two columns list the scenarios and ultimate emissions standards, while the next two columns list, respectively, the capital investments in millions of dollars in 1975 and the averages over the 1975-1979 time frame. Finally, the last column lists the average capital investment per car over the 1975-1979 period. To find the investment per car for a specific technology included in a given scenario, a more detailed study of the scenario must be made.^{7.5} This has been done in order to provide the investment contributions to the engine systems previously depicted in Table VI-4.

TABLE VII-3

Estimated Capacity of the U.S. Automotive
Tooling Industry in 1974, in Millions of Dollars

1. U.S. Capacity for Making All Types of Metal Cutting Transfer Lines	\$335
2. Total Capacity Appropriate to Automotive Operations (78% of Item 1)	\$260
3. Amount of Item 2 Exported	\$ 46
4. Amount of Item 2 Sold to Other Industries	\$122
5. Net Amount Used for Automobiles in 1974	\$ 92

Source: Reference 7.1

TABLE VII-4
Combinations of Engine Technologies and Standards Studied in Detail

Scenario	Emissions Standard	Ultimate Car Classes	Engine Technology	Calendar Year of Introduction	1980 Domestic Market Share	1983 Domestic Market Share
A	Federal 1970	22	Baseline Car	1969	100	100
C	Federal 1975/ California 1975	29	Conventional engine with air injection & EGR	1974	12	12
		36	Conventional engine with EGR & oxidizing catalyst	1974	47	47
		43	Conventional engine with EGR oxidizing catalyst, and air injection	1974	35	35
		50	Conventional engine with proportional EGR, oxidizing catalyst and air injection	1974	6	6
E-2	Federal 1977	50	As above	1974	100	100
ED-2	Federal 1977	50	As above	1974	88	83
		190	Diesel	1977	12	17
ESC-2	Federal 1977	50	As Above	1974	73	59
		85	CVCC with lean thermal reactor	1977	27	41
J	Federal 1978	71	Conventional engine with air injection and serial catalyst system	1977	64	46
		141	Conventional engine with EFI and three-way catalyst	1977	36	54

Source: Reference 7.3

TABLE VII-5

Annual Investment Costs of Meeting Various Emissions Standards under the Assumption of Table VII-4

Scenario	Emissions Standard (HC/CO/NO _x) ¹	Yearly Investment, Million \$ in 1975	Dollar/Car Average 2 1975-1979
A	Federal 1970 (3.9/33/6.0)*	0	0
C	Federal 1975 (1.5/15/3.1) California 1975 (0.9/9.0/2.0)	7	3.13
E-2	Federal 1977 (0.41/3.4/2.0)	20	5.87
ED-2	Federal 1977 (0.41/3.4/2.0)	50	6.51
HC-2	Federal 1977 (0.41/3.4/2.0)	20	10.27
J	Federal 1978 (0.41/3.4/0.4)	98	17.76

¹HC/CO/NO_x emissions given in g/mi.²Sales of 47,872,000 units are assumed over this period.*No standard existed for NO_x in 1970. This is an estimated emissions level for the average car.

Source: Reference 7.1

A number of conclusions can be drawn from these tables:

1. The presently mandated emissions standard for 1978 would require a capital investment level of about \$170 million per year if only dual-catalyst and three-way-catalyst systems were used (see Scenario J). This is 30% more than the average capital expenditure for emissions-control technology from 1970 to 1974 of \$130 million. Since only about half of this expenditure draws on the limited metal-cutting-transfer-line capability of the tooling industry, the somewhat higher level of capital expenditure should be no problem. Limited production facilities for carburetors adaptable to feedback control are being built in this country, but production facilities for fuel-injection systems exist only abroad.

2. If no new standards were introduced after the 1977 standard of 0.4/3.4/2.0 g/mi, then emissions-control investment costs need not rise significantly above the \$30 million-per-year level associated with continuation of the present standards since only rather minor modifications to existing technology are required. The \$30 million-per-year capital expenditures for emissions control after 1975 in Scenario C result from costs associated with the assumed 3.5% production growth rate and the projected shift to smaller cars.^{7.6}

3. Scenarios ED-2 and ESC-2 suggest that by 1980 diesel engines could become 12% of the domestic production or that stratified-charge engines could become 27% of domestic production within the normal bounds of capital expenditures by the industry.

As indicated earlier, if one goes beyond the normal levels of capital expenditures as were used as a bound for these scenarios, then stress is placed on the system in several areas, particularly the management skills and the tooling resources. While management limitations are a real constraint, there is no good way to quantify them. In the case of tooling resources, however, we have determined a level of capability for automotive work of about \$260 million per year, of

which about \$92 million was used by the automotive industry in 1974.

Tooling to mass-produce an entirely new engine at a rate of 300,000 units per year would cost about \$150 million, including the following approximate costs for various transfer lines: engine assembly, \$38 million; cylinder block, \$35 million; engine head, \$22 million; manifolds, \$9 million each; crankcase, \$11 million; rods and pistons, \$7 million each, etc.^{7.7} Thus, conversion of 30% of the domestic production to an entirely new engine would require a minimum period of four to five years. This assumes that all of the identified \$260 million of automotive tooling capability went into this effort, or about three times as much as was spent in 1974.

More rapid conversion can be postulated for engine systems which can be based on modifications of existing engines. For example, we have assumed that the domestic diesel production could be based on conventional engines in which the cylinder block would be strengthened but still produced on the same basic line, and that the CVCC and CCS engines would require only new engine heads, carburetors or fuel-injection systems, etc. In this way, we assume the investment costs for alternative-engine classes can be reduced to less than \$35 million per line. At a level of expenditure of \$260 million per year, it would still take four years to convert the entire domestic production to systems which are designed to use much of our existing tooling. Such a rate of conversion, if possible at all, would preclude using these tooling resources for farm machinery or for various other nonautomotive purposes which used two thirds of that resource in 1974.

VIII. FIELD PERFORMANCE AND MAINTENANCE

In order to determine the automotive contribution to air pollution, it is necessary to assess whether or not cars in actual use will meet the standards. The emissions of present cars will give some indication of how future cars will perform in the public's hands. However, conclusions about future systems must also take into account the expected effect of changes in technology on systems durability. Failures of emissions-control systems, as well as more rapid deterioration per mile in actual use, will increase the average emissions above those predicted by the certification test. Prevention by appropriate maintenance and diagnosis involving inspection will reduce the occurrences and effect of these failures.

The reliability of emissions-control systems vehicles that have been in service for a year or more can be determined from surveillance programs. However, the reliability of future emissions-control systems must be predicted by the data collected on a limited number of prototype vehicles that are put into fleet service. Fleet service is more representative of in-use operation than is certification testing, but does not represent typical customer use because fleet vehicles usually receive periodic, well-supervised maintenance which is not usually the case in customer service. It will therefore be necessary to view the fleet data with some caution. This is particularly significant at this time because of the installation of catalytic converters on some 1975 model cars; this requires the use of unleaded fuel. Due to significant differences in the systems, the catalytic converter is discussed separately from the noncatalytic systems.

A. Performance in Use

The best data on the emissions of privately owned vehicles come from the surveillance programs conducted by EPA and the California Air Resources Board. The average emissions levels obtained in the EPA exhaust-emissions-surveillance program for fiscal year 1972^{8.1} are presented in Table VIII-1.

TABLE VIII-1

EPA Exhaust Emissions Surveillance Program Results
 1972 Model Year Vehicles
 1972 CVS Test Procedure--Average Emissions Levels in (g/mi)

	<u>Number of Cars</u>	<u>HC</u>	<u>CO</u>	<u>NO_x</u>
Four-City Total	140	3.42	43.79	4.52
Denver	35	5.61	90.42	3.00
Los Angeles	35	4.07	55.77	3.83

Source: Reference 8.1

TABLE VIII-2

California Air Resources Board Surveillance Program
 Average Emissions Levels from Vehicles Hot-Start
 Tested on the Seven-Mode Cycle

<u>Model Year</u>	<u>Number of Cars</u>	<u>Average Mileage</u>	<u>HC g/mi</u>	<u>CO g/mi</u>	<u>NO_x g/mi</u>
1972	905	16,700	2.14	17.40	2.96
1973	445	10,500	2.12	17.85	2.77
1974	106	3,800	1.78	14.83	1.69

Source: Reference 8.2

The average emissions levels in the four cities (St. Louis, Chicago, Houston, and Washington, DC) were slightly above the applicable standards of 3.4 g/mi HC and 39 g/mi CO, but greatly exceeded the standards in Denver and Los Angeles. However, further results in this study showed that only 42% of the 1972 cars tested in St. Louis, Chicago, Houston and Washington, DC, were meeting both the HC and CO standards, only 29% in Los Angeles and only 3% in Denver.

The average emissions of 1972-1974 California cars hot-start tested on the seven-mode cycle from the California Air Resources Board surveillance program are given in Table VIII-2.^{8.2} The average mileage of the vehicles tested is also listed. The applicable California emissions standards for HC and CO are 1.4 and 19 g/mi, respectively, for all three years. The NO_x standard is 3.2 g/mi for 1972 and 1973 and is estimated^{8.3} to be 2.1 g/mi on the hot-start test for 1974. Figure VIII-1 is an illustration of the results of one of the Air Resources Board's evaluations.^{8.4} It can be seen from the amount by which the average HC and CO emissions of the vehicles in use exceed the standards that the durability of these emissions-control systems is not sufficient in the present maintenance regime. However, the general availability of unleaded fuel may well lead to greater use of this fuel in noncatalyst cars, leading to a reduction in maintenance requirements and reduction of emissions.

A significant problem is the deliberate deactivation of the emissions-control systems. The recent surveillance^{8.5} of 1974 vehicles in the Washington, DC, area showed that 15% of the 1970-1974 vehicles inspected had one or more emissions-control devices (carburetor emissions controls, EGR, vacuum spark retard, air injection, and crankcase controls) deactivated. A total of 33% exhibited some form of tampering with the emissions-control system. A similar study in New Jersey^{8.5} showed that 11% (out of 2,000) of the 1970-1974 vehicles sampled had emissions-control devices deactivated, with the percentage increasing with vehicle age up to 17% for 1970 models. The New Jersey study further showed that

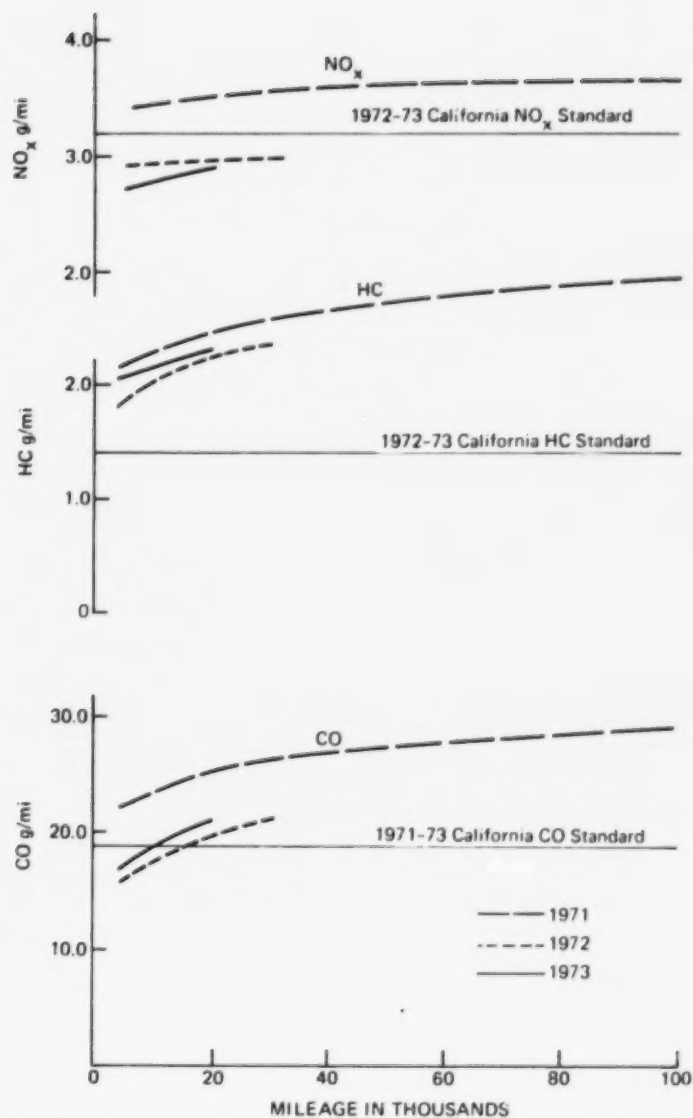


FIGURE VIII-1 Exhaust Emissions Versus Mileage, California Automobile Population 1971-1973 Models, All Tests Hot Start, Only 6% of the 1971 Vehicles Tested had Mileage Greater than 52,000 Miles. The Line Shown Therefore Represents an Extrapolation.

Source: Reference 8.4

vehicles on which tampering with the emissions-control system had been observed, had 98% more HC and 50% more CO idle emissions than the other vehicles. The smaller percentage of tampering reported in New Jersey may indicate the effectiveness of the inspection plan in operation in New Jersey.

B. Fleet Test Data on Catalytic Converter Systems

General Motors is conducting several field tests on experimental catalytic converters. Results^{8.6} on two taxicab fleets are shown in Figure VIII-2. Both groups used the under-floor catalytic converter for 1975 GM cars. Group 1 is designed to meet the 1975 Federal Emissions Standards and Group 2, the 1975 California Standards. Although neither fleet has completed 50,000 miles, the data indicate that these vehicles will meet the standards for which they were designed. These fleets were fueled from easily controlled central facilities and, consequently, the danger of catalyst activity loss from lead poisoning was minimized.

Ford placed 450 vehicles in lease-car fleets in California.^{8.7} This service was reasonably representative of customer service because the majority of the vehicles were in motor pools with a variety of drivers. Ninety of the vehicles received maintenance and were tested for emissions at the intervals recommended for the 1973 model year (0, 4, 12, 24, 36, and 48 thousand miles). The other 360 vehicles were tested only if unscheduled maintenance was performed which may have affected the emissions. The testing and maintenance was conducted by Ford personnel so that the care of these vehicles was probably better than would be expected from typical service personnel. The vehicles were fueled at commercial stations marketing both unleaded (less than 0.05 g/gal) and low-lead fuels (0.5 g/gal). There were 121 cases of misfueling, although 42 of these cases were realized before the vehicle was started. Confusion between the unleaded and low-lead fuels were responsible for some of the misfueling incidents.

The emissions results for the vehicles in the 90-car fleet, which did not require a catalyst replacement, are shown in Table VIII-3. Six

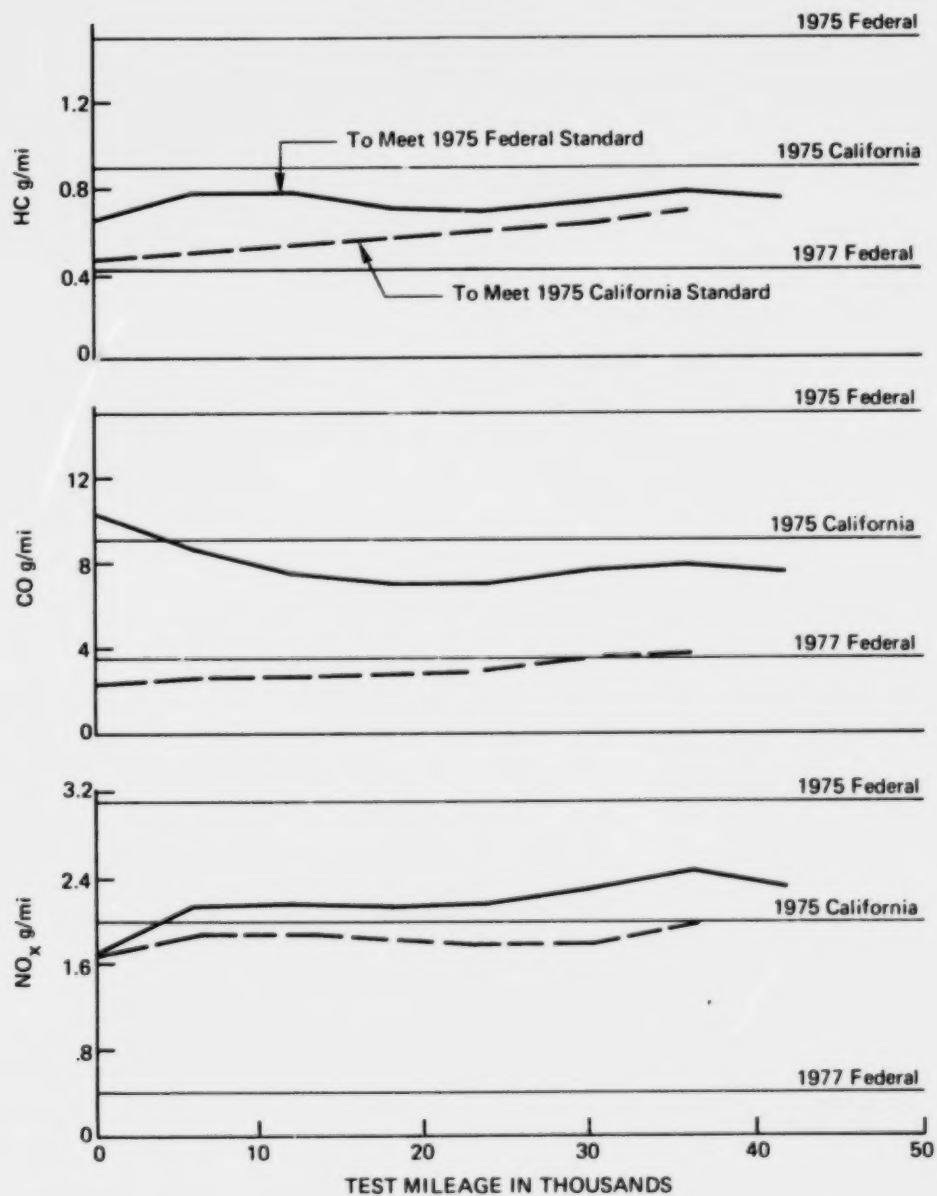


FIGURE VIII-2 Average Emissions Results on GM Catalytic Converter Fleet Vehicles.

Source: Reference 8.6

TABLE VIII-3

Emissions Test Results for Vehicles in the Ford 90-Car Fleet
Before and After Maintenance (1975 CVS Test)

Mileage	Number of Vehicles	Average Emissions (g/mi) - Standard Deviation		
		Before Maintenance After Maintenance	HC CO	NO _x
0	90	0.195-0.06	1.52-0.60	2.26-0.20
4,000	85	0.256-0.09	2.20-1.17	1.97-0.29
	86	0.245-0.11	1.86-0.87	2.07-0.24
12,000	82	0.328-0.17	2.56-1.27	2.01-0.25
	82	0.295-0.07	1.43-0.48	2.34-0.26
24,000*	43	0.410-0.28	3.22-1.61	1.91-0.32
	40	0.350-0.08	2.57-1.00	2.06-0.35

* Not all vehicles have reached this mileage.

Source: Reference 8.7

vehicles had catalysts replaced early in the test and another three at later stages. The emissions both before and after maintenance were tested and the standard deviation was calculated. A general trend in the data shows decreased HC and CO emissions and increased NO_x emissions after maintenance, although at the 95% confidence level most of the data were not statistically significant except the CO emissions at 12 and 24 thousand miles and the NO_x emissions at 12 thousand miles.

General conclusions from the tests were that: occasional catalyst temperature excursions above 1700 °F were not significant unless caused by total ignition loss; ignition failure was the most significant cause of catalyst melting; usually catalyst melting was incomplete and partially melted catalysts still significantly reduce HC and CO emissions; one tankful of leaded gas will not significantly affect emissions after about 200 miles on unleaded fuel service; and scheduled or unscheduled maintenance has a relatively insignificant effect in reducing HC emissions but reduces CO emissions and tends to increase NO_x emissions.

The number of catalyst failures^{8.8} in the 50,000-mile durability fleets appears to be quite small (about 3 or 4 in 200 cars), but it is difficult to obtain definite figures because some catalyst failures, which are blamed on engine malfunction of experimental systems, are excluded. Actual use in the customer's hands will be harder on the catalysts than the Durability Driving Cycle. Poorer control of the fuel quality and about 700 times as many starts and stops in 50,000 miles than in the official cycle will put a larger stress on the catalyst system. Whether the increased number of heat cycles had an effect is not known. However, the fleet-test vehicles did experience fuel problems similar to the ones that could occur in general use.

The taxicab fleets equipped with GM under-floor catalytic converters had four catalytic converter failures^{8.6} in a total of about 100 vehicles, all attributed to engine misfire. Fleets operated in Los Angeles, Phoenix and Pontiac all experienced fuel problems. The Los Angeles fleet experienced severe spark-plug fouling when fueled with gasoline containing twice

the normal amount of detergent. The Phoenix fleet had even more severe spark-plug fouling, which was traced to gasoline containing large quantities of higher-boiling components. A batch of gasoline with unusually high phosphorus content completely deactivated the catalysts in the Pontiac test and the test had to be restarted.

The 450-car Ford fleet had 17 catalytic converter failures,^{8.7} of which 15 were melting of the substrate and 2 were flange leaks. The substrate melting was attributed to total ignition loss under road load in each case; the causes are being corrected in 1975 production vehicles and the flange design has been improved. Nevertheless, these could represent the types of failure which occur as the result of improper maintenance. The totality of experience during the development of catalytic-control systems leads to the following list of field conditions which probably would cause catalyst failures:

- . Complete ignition failure at moderate to high speeds.
- . Misfires caused by ignition failures.
- . Severe dieseling.
- . Stuck choke.
- . Failure of coasting protection control.
- . Fuel which causes spark-plug fouling.
- . Fuel which directly poisons the catalyst.

Field experience with the fleets discussed above indicates that engine malfunctions which could lead to catalyst failures would be expected to occur in 3% to 4% of the car population by the time they reach 50,000 miles.

Spark-plug fouling by substandard gasoline or by abnormal oil consumption has already been discussed. A more frequent occurrence, particularly during the next year or two, may be the direct poisoning of the catalyst by the use of fuel containing lead or phosphorus. Phosphorus is a severe poison and instances of such poisoning will undoubtedly occur, but the frequency should be less than that for lead since it is only added to counteract some of the effects of lead on engine

deposits. Unless substantially more unleaded gasoline is produced than is required to fuel the 1975 cars, local shortages may result in use of leaded fuel, which will cause rapid deterioration of the oxidation catalysts.

There are no hard data to show what percentage of the catalytic converters will be inactive because of the combination of the above possible causes. Proper maintenance should hold the percentage below 5% in the car population by the time they reach 50,000 miles. However, if the failures are not detected and corrected soon after they occur, the percentage of inactive catalysts in the car population would be larger as the result of the combined effects of all causes.

C. Performance and Maintenance of Emissions-Control Systems

The performance of emissions-control systems is difficult to define because of the widely different use patterns of automobiles and the varying degrees of maintenance received. Any definition of durability must be coupled with the maintenance level experienced. Different levels of maintenance of interest are the following: the maintenance received during certification testing, the maintenance received in fleet use, some form of mandatory-inspection-and-maintenance, and maintenance in actual use by the public. We have actual experience with 1975 systems on only the first two levels, as discussed in the previous part on Performance in Use. Predicting the performance of the present and future emissions-control systems is much more difficult because of the unknown durability of the control systems and the uncertainty in the maintenance regime that will be in force. Basic durability of the emissions-control systems to be introduced in 1975 appears to have improved, judging by the fleet-vehicle performance data. Because of the use of unleaded fuel, the performance of these systems in service is likely to degrade less than those in previous years.

Several improvements have been made in the 1975 vehicles which increase the life of the control systems and decrease the need for maintenance. Many of these relate to the use of unleaded fuels. The absence

of lead results in the following advantages:^{8.9}

- . EGR valves require no service for 50,000 miles because of the slower rate of deposit build up,
- . Spark-plug life is about doubled, partly due to the use of ignition systems with higher energy,
- . The required interval for service of the heat-riser valve is extended by a factor of 4 to 5, and
- . HC and NO_x exhaust emissions from the engine, before any catalytic treatment, are lower by about 0.75 g/mi.

At least one manufacturer is sufficiently convinced of the advantages of unleaded fuel that all of its 1975 vehicles will be designed to accept only unleaded fuel, including those models which will have noncatalytic-control systems.^{8.9}

Catalysts and catalyst containers have also been improved to obviate the need for catalyst replacement before 50,000 miles at least on all domestic vehicles. The tolerance of catalytic converters to ignition misfire has been improved. Most systems can tolerate a misfire on up to 25% of the cylinders feeding a single catalyst at normal operating conditions. Single catalysts serving six or eight cylinders can withstand misfires of one cylinder under any condition.^{8.9}

An important inspection tool to consider with a catalytic converter is a functional test to determine if the catalyst is active. The manufacturers' recommendations do not include such a test. Also omitted from manufacturers' recommendations is a means of sampling the exhaust gas ahead of the catalyst so engine malfunctions can be diagnosed by the aid of infrared analysis.

Ignition systems and fuel-system components have also been improved to help prevent either ignition or lean misfires that could lead to failure of the catalyst. These improvements include:

- . Electronic ignition systems that eliminate the rubbing block-type breaker points in the distributor. This minimizes point failures and changes in spark timing.

- . High-tension ignition wires and connectors with greater thermal resistance.
- . Ignition systems with greater tolerance to water.
- . In many cases, ignition systems with higher spark energy and larger spark-plug gaps. This results in longer spark-plug life.
- . Fuel pumps with greater reliability and life.

The improvements in the ignition system will also increase the probability of the noncatalytic-control systems meeting the standards.

D. Effect of Emissions-Control Failure on Average Emissions

Untreated exhaust which is emitted from any vehicle will increase the average emissions of the fleet and, thus, reduce the probability of meeting the standards on average. The effects of such failures on average emissions have been analyzed using the following simplifying assumptions:

1. The average 1975 vehicle that has not suffered a complete emissions-control failure will have the weighted average emissions at 50,000 miles as listed in Table IV-1. This neglects the fact that in use deterioration may be greater than suggested by the 50,000-mile durability test because of more cold starts and a greater aging process.
2. The average vehicle designed to meet the Federal 1977 and 1978 Emissions Standards, which has not suffered a complete emissions-control failure, will have 0.8 times the permitted emissions at 50,000 miles. This value was selected because it is slightly smaller than the smallest safety factor the manufacturers have built in to date. These certification emissions levels as a fraction of the standard are listed in column three of Table VIII-4.
3. The uncontrolled exhaust from an average car with total emissions-control failure is about 2.5 g/mi HC, 18 g/mi CO

TABLE VIII-4

Effect of Failures of System on Average Emissions
in g/mi at 50,000 Miles

	Emissions Standard	Certification Emissions Level as Fraction of Standard	Failure of Cat. or EGR	Calculated Emissions at 50,000 Miles for Given % Failure			
				0% Fail	5% Fail	10% Fail	20% Fail
Fed. 75	1.5/15/3.1	0.53/0.55/0.76	Both	0.80/8.2/2.4	0.87/8.7/2.5	0.96/9.2/2.7	1.14/10.2/2.9
Calif. 75	0.9/9.0/2.0	0.64/0.62/0.78	Both	0.58/5.6/1.6	0.67/6.2/1.8	0.77/6.8/1.9	0.96/8.1/2.3
Fed. 77	0.4/3.4/2.0	0.8/0.8/0.8	Both	0.32/2.7/1.6	0.43/3.5/1.8	0.54/4.2/1.9	0.76/5.8/2.3
Fed. 78	0.4/3.4/0.4	0.8/0.8/0.8	Cat.	0.32/2.7/0.36	0.43/3.5/0.44	0.54/4.2/0.52	0.76/5.8/0.69
"	"	"	EGR	"	0.32/2.7/0.39	0.32/2.7/0.41	0.32/2.7/0.47
"	"	"	Both	"	0.43/3.5/0.59	0.54/4.2/0.8	0.76/5.8/1.29

Note:
NO_x emissions of 0.36 g/mi with a 2.0 g/mi input implies an average catalyst efficiency of 82%. If average efficiency drops below this level, due to the rigors of customer usage or failure to make scheduled replacements, then the emissions from "non-failed" systems would be higher (e.g., 0.5 g/mi with 75% efficiency, 0.6 g/mi with 70%, 0.7 g/mi with 65%, etc.).

and 5.0 g/mi NO_x .^{8.8} This is probably a little worse than the actual case, since even melted catalysts may retain some conversion efficiency.^{8.7}

4. Cars meeting the Federal 1978 Emissions Standard use only catalysts to control HC and CO, but use EGR to achieve a NO_x input to the catalyst of 2.0 g/mi.

In Table VIII-4, the last four columns indicate the fleet average emissions that would be expected at 50,000 miles if there were 0%, 5%, 10% and 20% failures, respectively, using the preceding assumptions. The average emissions from zero to 50,000 miles would, of course, be less than this, and from 50,000 to 100,000 miles somewhat higher. The 50,000-mile point does, however, have some legal significance and does represent the midpoint in the average car's useful life.

Total system failures, only, are considered for Federal 1975, California 1975, and Federal 1977 Emissions Standards. Since for these standards HC and CO are controlled by the catalyst and NO_x by EGR, it is possible to infer from Table VIII-4 what would happen if a different failure rate were assumed for EGR than for catalysts. Since both EGR and a catalyst are assumed to be required to meet the NO_x level of 0.4 g/mi in 1978, cases were considered in which the different systems failed independently of each other.

From the table, it is clear that this analysis predicts that the 1975 Federal and California cars will, on average, meet the standards at 50,000 miles even if 10% of them have suffered complete emissions-control failures. In spite of the probability that deterioration in use will exceed that measured in the durability test, we judge that these cars will, on average, meet the standards in use even with the expected maintenance.

Similarly, the NO_x emissions for Federal 1977 vehicles are expected to be met in use. A 5% failure rate would cause the HC and CO levels for 1977 and 1978 to be exceeded by a negligible amount and a 10% failure rate would cause standards to be exceeded by 30% or less. For NO_x emissions an EGR failure rate of 10% would not place average 1978 emissions over

standards by 50,000 miles, but a 10% failure rate for catalysts would result in average emissions 30% higher than the standard.

The situation may be substantially worse than this analysis suggests if the durability of reduction catalysts is not improved sufficiently to make a specified replacement before 50,000 miles unnecessary. If this replacement is not mandatory then the average efficiency of catalysts at 50,000 miles would be lower than the calculation assumes with resultant emissions even from cars with "operative" emissions-control systems being above the standards as indicated in the note at the bottom of Table VIII-4.

E. Inspection and Maintenance Programs

The Clean Air Act delegates primary responsibility for controlling emissions from motor vehicles in actual use to the States.^{8.10} However, as part of the implementation plans for 12 States, the EPA has designated 19 metropolitan areas which must have mandatory inspection-maintenance programs. Among these are Chicago, New York, Los Angeles, and Washington, DC.

A review of progress in mandatory programs for ensuring proper maintenance has revealed that these programs have generally been delayed in implementation, although there appears to be continuing progress in many. For instance, the New Jersey emissions-inspection program was instituted in July 1972, but mandatory repair of failed vehicles was delayed until February 1974. A total of 3.8 million vehicles have been tested to date. The current rejection rate is 12% and this will be raised to about 24% by February 1, 1975.

Other programs that are in the planning or limited operational stages are the following:

- . Arizona is operating a prototype program in two counties, with 1976 the expected starting date of the full program.
- . California has legislation calling for a pilot emissions-inspection system in the six counties of the South Coast Air Basin. The scheduled starting date for mandatory emissions inspection is January 1, 1977.

- . Chicago is operating an idle-emissions test program, but the starting date for mandatory inspection has been postponed one year to June 1, 1975.

Some States have legal authority to perform emissions inspection, but have not yet implemented a program due to political opposition. Examples are New York and Pennsylvania. Washington, D.C. has had regulations authorizing inspection of vehicles for the deactivation of devices since 1968 but does not appear to have enforced them adequately as evidenced by the number of devices deactivated as discussed earlier.

There has been considerable delay in implementing mandatory inspection and maintenance programs. The political actions which either opposed or delayed programs in this area are undoubtedly reflections of underlying social attitudes and beliefs. Universal distrust of mechanics is of extreme importance. The only places where we have been told this does not exist are Japan and Canada^{8.11} where mechanics are licensed or controlled by the government.

Since most areas in the United States do not have governmental jurisdiction for enforcing proper maintenance, and considering the delays which have occurred in existing plans, it appears unlikely that it would be possible to implement a nationwide inspection and maintenance program in less than five years.

Of prime importance to emissions-control-system maintenance is an adequate service industry in terms of the numbers of mechanics, their competence and training, and the service facilities available. The Automotive Service Industry Association (ASIA) estimates the total number of mechanics in the United States at about 850,000, in fair agreement with the Bureau of Labor Statistics number of 800,000 based on the 1970 census. However, only about 500,000 of these mechanics are available to work on private automobiles since 265,000 are employed by government agencies, public utilities, etc. If the National Institute for Automotive Service Excellence (NIASE) test is taken as a measure of competence, then it is estimated that about 200,000 mechanics could pass

the test.^{8.12}

How many mechanics are required? In Japan, there are 74 vehicles per mechanic, and in England, the number is 68. At the National Automotive Service Vocational Education Conference in 1973, the number of 87 vehicles per mechanic was considered proper. If 87 is taken as the proper ratio of vehicles to mechanic then this implies a mechanic work force of 1.16 million to service the 101 million passenger vehicles in the United States. It has been estimated that only one-third of the mechanics are needed for tune-up and emissions-control work, which would mean 388,000 mechanics are necessary. Comparing this number to the rough estimate of the number of competent mechanics shows that it is necessary to double the present supply of competent mechanics.

Most of the dealerships and better service garages have all of the required equipment except infrared analyzers, so the equipment problems should offer difficulty only in the smaller shops. Perhaps more difficult to achieve, but even more important, is the creation of a work environment and operating philosophy that encourages good work. Certification and training programs could be helpful here. Two large industry groups^{8.12} are actively backing voluntary certification through the NIASE tests, and the number of persons registering for the NIASE tests is increasing.

IX. AUTOMOTIVE FUELS

A. Unleaded Gasolines

Historically, lead alkyl compounds have provided an inexpensive and effective means for improving the octane quality of motor gasolines, thus permitting combinations of engine compression ratio and ignition timing, giving good fuel economy and/or vehicle performance.

1. Emissions and Fuel Economy for Lead-Tolerant Versus Lead-Intolerant Vehicle Systems

Since 1970, average engine compression ratios in the United States have been reduced from about 9.5:1 to 8:1 in order to reduce NO_x emissions and permit the use of gasolines with reduced or no lead alkyl content.^{9.1} The estimated fuel economy penalty for this drop is about 6% at current gasoline prices, which represents an average added expense to the motorist of \$20 to \$40 per year.^{9.2,9.3} This will be offset by a nearly equivalent savings in reduced maintenance costs (improved spark-plug and exhaust-system life and reduced lube-oil expense) with unleaded gasolines, as discussed in Section VI.

The noted compression ratio reductions, coupled with retarded ignition timing, have occurred partly in response to the projected availability in 1975 of unleaded gasolines of 91 RON/83 MON octane quality. However, reductions in hydrocarbon (HC) and nitrogen oxide (NO_x) emissions produced by such engine changes have also been a compelling factor.

For emissions standards equal to or more stringent than the 1975 Federal interim regulations, lead-intolerant systems using catalytic exhaust converters exhibit better fuel economy than lead-tolerant thermal-reactor systems--even when the latter are operated with high compression ratios to take full advantage of lead antiknock additives.^{9.4,9.5,9.6} Optimization of the air/fuel ratio, ignition timing, and exhaust gas recirculation permitted by the use of catalytic converters more than offsets the noted fuel economy debit associated with the use of low-octane unleaded gasolines.

2. Alternative Engine Technology and Fuel Octane Quality

Promising prechamber engines of the CVCC type using lean thermal reactors appear to be lead tolerant. However, maximum compression ratio and ignition advance (and, hence, octane requirement) for these engines are limited by HC and NO_x emissions.^{9.7} As a consequence, the octane benefits of leaded gasolines are not realized in practice.

Leaded gasoline grades do not appear to be needed for development of promising advanced or alternative engine technologies. The most promising future power plants, including PROCO, CCS, CVCC, diesel, and gas turbine, have either modest octane requirements or no octane requirement.^{9.8}

3. Costs of Unleaded Gasolines

The incremental processing cost for raising the average clear-pool octane quality in the U.S. to the 91 RON/83 MON level is estimated at about 0.5¢ per gallon. This, of course, does not reflect added supply and distribution costs for an unleaded grade during the period of transition to unleaded gasolines, which could add as much as 1¢ to 2¢ to the price at the pump.^{9.9} A significant fraction of the incremental processing cost will be offset by reduced lead additive purchase costs.

The incremental increase in refinery energy consumption as crude loss is estimated at less than 1% for raising the clear pool to 91 RON/83 MON octane quality. The additional energy cost to produce a premium grade unleaded gasoline is estimated at 2%.^{9.9-9.13}

4. Toxicity of Lead Compounds Exhausted from Automobiles

Strong geographical and temporal correlation exists between airborne lead levels and automobile traffic density. The automobile is presently by far the greatest single contributor to airborne lead--about 98% of all lead traceable to specific sources comes from gasoline combustion.^{9.14}

The toxicological significance of long-term human exposure to present urban airborne lead levels is not known. Exposure of certain categories of workers to airborne lead from automobiles apparently leads to increased blood lead levels and is of concern. Also, the excessive blood lead levels in groups of children living in large cities points to lead particulate inhalation or ingestion and may represent a health threat.^{9.14}

5. Other Antiknock Additives

In addition to lead alkyls, there exist other classes of additive materials known to improve gasoline octane quality. However, large-scale introduction of such materials in the future would have to be preceded by thorough testing for compatibility with exhaust emissions-control systems and also for any direct effects of additive materials on the toxicity of exhaust gases.

Manganese compounds (methylcyclopentadienyl manganese tricarbonyl) have been advocated for use at low concentrations in unleaded gasolines. A one-to-two-octane-number benefit is envisioned.^{9.15} Testing for compatibility with catalytic exhaust converter systems is now under way. Manganese appears in vehicle exhaust as Mn_3O_4 .^{9.16} The small quantities of unburned additive that are exhausted decompose rapidly in sunlight to a mixture of manganese oxides and carbonates. The environmental impact of these emissions is now under study.

Recently, a cerium-based compound has been identified as a potential antiknock.^{9.17} Considerably more research is needed to establish general octane performance of this compound, as well as emissions-control system compatibility, basic-engine compatibility, and exhaust toxicity.

6. Summary

a. At exhaust-emissions levels required by present and future standards, lead-tolerant vehicle systems appear to have poorer fuel

economy than the lead-intolerant systems using exhaust catalysts. In addition, real savings in vehicle maintenance costs can be claimed for use of unleaded gasoline. On balance, the present trend toward an unleaded gasoline situation appears justified.

b. Alternative power plants that look promising for the future appear to have modest octane requirements or no octane requirement and, therefore, will not benefit from lead antiknock additives.

c. The toxicological impact of lead particulate emissions is not certain. However, a direct health benefit from reduction in airborne lead cannot be ruled out.

B. Alcohol Fuels

1. Straight Methanol

Of all the alternate fuels which have been suggested, the one that has been given the most consideration as the candidate most likely to supplement normal hydrocarbons is methanol. It is now feasible to convert coal to methanol and, in the minds of some, when fission or fusion energy becomes abundant this energy could be used to generate hydrogen, which would be converted to methanol again through the commonly accepted techniques using methanation catalysts.

Methanol has some very interesting characteristics as an automotive fuel. It burns at low temperatures without any particulate formation. Thus, one would expect that the combustion process in the cylinder could proceed very efficiently without appreciable NO_x formation. Indeed, laboratory tests show that under steady-state, warmed-up engine operating conditions, use of straight methanol can give substantial reductions in unburned HC, CO and NO_x emissions.^{9,18} Another advantage of methanol is that it would permit the return to high-compression-ratio engines. The methanol molecule is a tightly bound one and thus is not as prone to chemical or pyrolysis reactions during compression as in gasoline; i.e., high-compression-ratio engines

which use methanol as a fuel will not knock. Essentially, it has a high octane number, but it is not an antiknock compound.

Cold-start vehicle emissions tests (FTP) generally confirm the NO_x emissions benefits of methanol; however, unburned fuel emissions can exceed those obtained with gasoline.^{9.18} This disadvantage is most likely tied to the extremely high latent heat of vaporization of methanol, and the need for an excellent carburetion system. This high heat of vaporization can cause a serious fuel vapor and distribution problem within the engine. Major engine and fuel-system design changes would be required to provide adequate vehicle driveability and reliable cold-start characteristics.^{9.19} More work will be required to establish satisfactory solutions to the cold-start problem. (Gasoline volatility characteristics are carefully tailored on a geographic and seasonal basis in order to provide adequate vehicle operating characteristics.)

Methanol has two other inherent disadvantages: first, its low heating value, which is one half that of gasoline and which would require double the present size of gasoline tanks for roughly the same range; and, second, its corrosiveness to several materials presently used in vehicle fuel systems. To compensate for the corrosiveness, suitable alternatives to these materials would have to be provided.^{9.19}

2. Methanol-Gasoline Blends

Blends of 10% to 15% methanol in gasoline have been proposed as effective fuel supply extenders during times of petroleum shortage. The basic vehicle engine can operate satisfactorily on blends containing these amounts of methanol. Methanol has the advantage of a high-blending octane number. However, from an overall standpoint, many of the problems found with straight methanol persist, and new problems associated specifically with blending appear.

These include the following:

- . Ten percent methanol in gasoline gives a 6% shift in stoichiometry and necessitates

carburetor recalibration. Since air/fuel stoichiometry varies substantially with methanol concentration, accurate proportioning of methanol in field distribution systems would be mandatory to maintain low emissions levels.

- . A number of materials used in present fuel systems are subject to corrosion by methanol.
- . Contact with even small amounts of water can lead to a phase separation both in distribution systems and in the vehicle fuel system and, thus, can lead to serious problems with vehicle operation. Methanol is hygroscopic, so that contact with atmospheric water vapor can lead to sufficient water adsorption to give phase separation. Some have argued that the presence of aromatics in the fuel alleviates the separation problem.
- . Methanol solubility in gasoline varies widely with temperature and gasoline hydrocarbon composition. Solubility problems could be encountered with widespread use of methanol blends.

Substantial reductions in exhaust emissions have been claimed for methanol-gasoline blends. These reported changes appear to have resulted from the simple leaning effect associated with methanol stoichiometry. In late-model vehicles with carefully calibrated carburetors, this effect can impair driveability and possibly increase HC emissions.^{9.20}

In summary, use of methanol-gasoline blends can lead to a number of serious and varied technical problems. Solutions would involve considerable expense and a major commitment to methanol use. Neither can be justified from the standpoint of exhaust-emissions benefits alone.

3. Higher Alcohols

Ethanol, propanol, and t-butyl alcohols have gasoline-blending characteristics superior to methanol. These materials can be used successfully in gasoline blends with existing conventional gasoline engines.^{9.21} Several major U.S. refiners have marketed gasolines containing t-butyl alcohol. Blends containing these higher alcohols do not offer significant emissions advantages, though real antiknock benefits have been reported.

C. Hydrogen

From the standpoint of exhaust emissions alone, hydrogen is an excellent fuel. With pure hydrogen, HC and CO emissions arise only from lubricants and are practically nonexistent, and NO_x emissions can be reduced substantially through lean-mixture operation. Assuming that adequate supplies of hydrogen could be made available, major problems would be encountered in the areas of vehicle-hydrogen storage and engine combustion.

On a volumetric basis, almost 20 times as much compressed hydrogen as gasoline would be required for equal vehicle range. Four times as much liquid hydrogen as gasoline would be required. Solid hydride storage systems have been proposed; however, the weights involved are prohibitive.^{9.22} The combustion characteristics of hydrogen differ substantially from conventional fuels and would necessitate major engine and fuel-system design changes. As commonly realized, hydrogen has excellent combustion characteristics.

Use of hydrogen-gaoline mixtures permits combustion with extremely lean air/fuel ratios. As a consequence, NO_x and CO emissions can be reduced to levels consistent with statutory emissions standards. However, the low exhaust temperatures associated with this type of engine operation can lead to excessive HC emissions.^{9.23}

Several onboard reformer systems for conversion of part of a vehicle's gasoline supply to hydrogen have been proposed.^{9.24} Progress has been encouraging; however, major problems exist in two areas: overall system thermal efficiency and excessive HC emissions. These programs are in early stages and further work will be required to evaluate the potential for this concept.

D. Other Gaseous Fuels

Commercial equipment is available for conversion of vehicles to use compressed natural gas (CNG) or liquefied petroleum gas (LPG). These gaseous fuels can be of benefit in reducing HC and CO emissions under cold-start conditions when conventional liquid fuels require mixture enrichment to form a flammable mixture.

Claims for NO_x emissions reductions have been made. However, it appears that with engines tuned for equal performance and economy, NO_x emissions with these gaseous fuels are approximately equivalent to emissions with gasoline.^{9.25}

In addition to problems with supply logistics, these fuels suffer from limited vehicle range. Their widespread use would require special attention to a different set of fire safety problems. Since most, if not all, of the emissions benefits of these gaseous fuels can be equaled with late-model-vehicle systems using conventional gasolines, there does not appear to be an incentive for large-scale conversion to gaseous fuel systems.

E. Water-Fuel Mixtures and Emulsions

Introduction of water into both gasoline and diesel engines, either

by means of special injection systems or in the form of water-fuel emulsions, has received varying levels of attention for many years. In gasoline engines operating with extremely low-octane fuels, water can reduce audible knock. However, with engines of modern design and gasolines of present octane quality, the antiknock benefits do not appear great enough to justify the costs and probable inconveniences of large-scale water use.^{9.26}

Water introduction reduces NO_x emissions in the same manner as EGR;^{9.27} but by comparison, water induction involves significantly more expense and inconvenience and appears to offer no functional advantage over EGR. In some cases, water-fuel emulsions have appeared to reduce carbon monoxide emissions. This generally results from the simple carburetor leaning effect produced when water displaces part of the metered-fuel volume. In late-model vehicles with precise carburetor calibrations, this effect would be expected to impair driveability and probably increase the emissions of unburned hydrocarbons.

Recently, it has been discovered that some emulsions will undergo micro-explosions when droplet combustion begins. Such explosions decrease the heterogeneity of the combustion process, and, it has been argued, will reduce all emissions, including particulates. Although possibly having some effect on spark-ignition engines, this phenomenon could be of great significance in reducing NO_x and particulate emissions in the diesel engine. Research in this area is just beginning.

F. Sulfur Emissions and Fuel Sulfur

1. Gasoline-Powered Vehicles

In conventional gasoline engine systems (pre-1975), the sulfur contained in the fuel is exhausted primarily as SO_2 . At present, the SO_2 from automobiles is not considered a local hazard. Further, gasoline sulfur content is generally less than 0.1% and, as a consequence, vehicle SO_2 emissions represent a small contribution to total airborne sulfur.^{9.28}

Preliminary tests have shown that exhaust oxidation catalysts as installed on 1975 vehicle prototypes may convert a substantial fraction of fuel sulfur to sulfuric acid or sulfate materials.^{9.29} Again, emissions of these materials constitute a relatively small proportion of total atmospheric sulfur. However, there is concern that local concentrations in regions of high traffic density may constitute a health hazard, and it may be necessary to consider reduction of gasoline sulfur levels in the future. This problem is under surveillance by the EPA. It has been estimated that the cost of reducing the sulfur content of gasoline from 0.03% to as low as 0.003% would cost from 1¢ to 2¢ per gallon and would result in an increase in refinery energy consumption of about 0.4%.^{9.9}

2. Alternative Power Plants and Sulfur Emissions

It is expected that CVCC-type stratified-charge engines equipped with thermal reactors will emit fuel sulfur primarily as SO_2 . Therefore, these engines will not have a sulfate emissions problem.

Ford PROCO and Texaco TCCS engines both depend on oxidation catalysts for HC control. As a consequence, reduction of fuel sulfur for these engines may be necessary. This problem is particularly important with respect to the CCS systems operating successfully on distillate fuels, which presently contain about ten times more sulfur than do motor gasolines.

For diesel engines, fuel sulfur is emitted primarily as SO_2 ,^{9.30} and, as a consequence, fuel sulfur levels as high as those of present motor gasolines can probably be tolerated. However, should large-scale conversion to diesel engines take place, the present level of sulfur in diesel fuels may not be acceptable.

X. TEST METHODS AND PROCEDURES FOR EMISSIONS AND FUEL ECONOMY

A. Introduction

The reliability and reproducibility of both emissions and fuel economy data are strongly influenced by the specified test methods and procedures. The CVS-CH test method--which defines a driving cycle, weighting factors for the three test phases, and experimental procedures--plays an important role in the certification process for 1975 and subsequent model-year, light-duty motor vehicles (LDMV's). Since emissions are dependent both on the driving cycle and on the test-phase weighting factors, it is important to evaluate the extent to which these aspects of the test approximate real-life conditions in an urban area. Both systematic and random errors associated with vehicle and test variability play an important role in determining mean design emissions levels for a family of vehicles that are to be manufactured to meet specified emissions standards.

The following material on emissions discusses the adequacy of the CVS-CH driving cycle and test-weighting factors, the magnitude of variability in exhaust-emissions tests, and the factors that affect the statistical variability of emissions tests. These results indicate that some changes could be incorporated in the present CVS-CH test which would reduce the statistical variability associated with emissions tests. Finally, data are presented which indicate that evaporative hydrocarbon losses may contribute significantly to the total HC emissions from light-duty motor vehicles. These results indicate that the test method presently mandated by EPA to determine evaporative emissions is inadequate.

The development of a rational energy conservation strategy for the transportation sector requires, among other things, a detailed understanding of the factors that influence automotive fuel economy and the development of standardized fuel economy test methods and procedures. One short-term need is to assess the validity of present fuel economy tests. A medium-term need is to develop a standardized fuel economy

test method and procedure that can be applied to standard patterns of driving and mileage accumulation. A long-term need is for a more accurate data base which can be employed to make projections of the effects of changes in vehicle technology and use patterns on total U.S. fuel consumption.

The critical elements in any standardized fuel economy test method and procedure include: a representative standard driving cycle or cycles; a method to determine the mass or volume of fuel consumed and the distance traveled during the test; and a procedure for simulating vehicular loads encountered during the course of the driving cycle. The following material on fuel economy considers each of these critical elements. In addition, the statistical variability associated with present fuel economy test methods is considered.

B. Certification Procedures, CVS-CH Test

In order to enforce the provisions of the Clean Air Amendments of 1970, emissions standards have been established and EPA has established the official CVS-CH test method and regulations prescribing requirements a manufacturer must meet before EPA will grant a Certificate of Conformity. A Certificate of Conformity is required before a manufacturer can produce and sell a specific class of light-duty motor vehicles.

The CVS-CH test method, which defines a specific driving cycle, weighting factors for the three test phases, and experimental procedures, is employed to determine the true mass emissions of 1975 model-year and later vehicles. The CVS-CH test method consists of a 12-hour soak at a temperature between 60° and 86°F, a cold-engine start-up, a continuous sequence of different driving modes simulating an average trip over a 23-minute route in an urban area, a ten-minute shutdown followed by a hot-engine restart and a repeat of the first 505 seconds of the 23-minute cycle. This test is performed with the vehicle on a chassis dynamometer. Exhaust-gas sampling begins immediately after the key is

turned on, whether the engine starts or not. Diluted exhaust emissions are collected during the first 505 seconds in one bag, those during the remainder of the 23-minute cycle in a second bag, and those from the hot-restart phase in a third bag. Contents of the three bags are then analyzed and weighted in accordance with the EPA test procedure to determine the final mass emissions, in grams per mile, of HC, CO and NO_x. In addition to exhaust emissions, evaporative HC emissions are measured during the course of the CVS-CH test method by collecting evaporative emissions in carbon canister traps and measuring the weight of fuel absorbed during the "diurnal," "running" and "hot-soak" phases of the test. Details of the Federal Test Procedure may be found in References 10.1 and 10.2.

In order to obtain a Certificate of Conformity for a class of vehicles, the manufacturer must demonstrate that the vehicles meet the appropriate emissions standards over the "useful life" of the vehicle, which is defined to be 50,000 miles. The regulations require a manufacturer to test two separate fleets of prototype vehicles representing models to be sold to the public. The emissions-data fleet is intended to determine the emissions of relatively new vehicles. The vehicles in this fleet are driven 4,000 miles to break in the engine and stabilize emissions. The emissions are then measured, using the CVS-CH test procedure. Allowable maintenance on emissions-data vehicles is limited to the adjustment of engine idle speed at the 4,000-mile test point.

The second fleet, the durability-data fleet, is designed to determine the capability of the emissions-control system to keep emissions below the standards over the expected useful life of the vehicle. Each engine-system combination in the durability-data fleet is examined separately. The vehicles are driven for 50,000 miles and tested for emissions every 5,000 miles. The procedure for mileage accumulation is the Durability Driving Schedule over a modified AMA route. The maximum speed is 70 mph, and the average is 30 mph. Scheduled maintenance of

durability vehicles may be performed at the same mileage intervals as specified to the consumer. Scheduled major tuneups to manufacturer's specifications may be performed no more frequently than every 12,500 miles. The replacements and adjustments allowed are detailed in the regulations. Emissions tests must be run before and after any vehicle maintenance that may be reasonably expected to affect emissions. The manufacturer has the option of running more than one durability-data vehicle in each engine-system combination and up to three valid CVS-CH tests at each mileage point may also be run provided that the same number of tests are conducted at each mileage interval. Once a durability-data vehicle is started in the fleet it must continue to operate unless discontinued by written consent of the EPA Administrator.

All the data generated for each engine-system combination are used to compute separate deterioration factors for HC, CO and NO_x for each engine-system combination in the durability-data fleet. The emissions data are plotted as a linear function of mileage and the best straight lines, fitted by the method of least squares, are computed for each set of data. The interpolated 4,000- and 50,000-mile points of the lines must be within the specified emissions standards or the data cannot be used for the calculation of a deterioration factor. Deterioration factors for each of the three pollutants, for each engine-system combination, are subsequently computed by taking the ratio of the emissions at 50,000 miles to the emissions at 4,000 miles for the appropriate least squares fit.

Each car in the emissions-data fleet is subsequently tested for certification by multiplying its exhaust-emissions test results by the appropriate deterioration factors to obtain the adjusted emissions for the vehicle. These adjusted emissions are then compared to the standards and if the adjusted emissions for all pollutants are below the appropriate standards the car passes; if not, it fails. In the event that the car fails, it may be tested a second time. If the car passes the second test, it is considered to have met certification. Every

emissions-data car in an engine family must pass the test before the family can be certified.

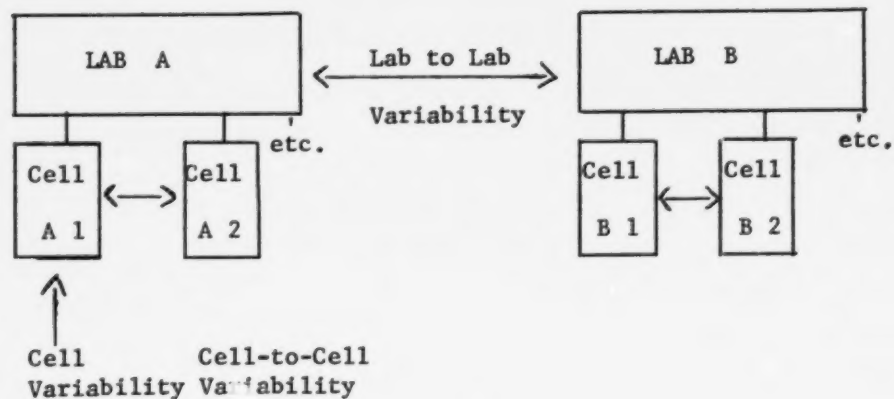
C. Exhaust Emissions

1. CVS-CH Driving Cycle

The driving cycle associated with the CVS-CH test method, the urban dynamometer driving cycle (UDDS), was developed to simulate driving patterns in an urban environment.^{10.3} More recent studies have been carried out in five major metropolitan areas to determine if the UDDS is an adequate representation of urban driving.^{10.4 to 10.7} These studies indicate that the UDDS has a lower average speed and a higher percentage of time in the idle mode than the five-city composite cycle. However, it has been reported that there are not significant differences in exhaust emissions of vehicles tested in the five-city composite cycle when compared to the UDDS.^{10.8} Based on these results, it is concluded that, on balance, the CVS-CH test cycle is a sufficiently accurate representation of urban driving patterns to be used for purposes of determining light-duty motor vehicle exhaust emissions.

2. Statistical Variability of Exhaust-Emissions Measurements

Both systematic and random errors associated with vehicle variability, emissions collection and measurement variability, and environmental variables contribute significantly to the test variability for a single vehicle. In addition, variations in emissions from a group of similar production vehicles are important. There are three levels of variability associated with the measured exhaust emissions for a given vehicle (see Figure X-1). These are the variabilities associated with a given test cell, cell-to-cell variability within a given laboratory site; and the laboratory-to-laboratory variability. The most important factors affecting exhaust-emissions variability at each of these levels are also listed in Figure X-1. An estimate of CVS-CH exhaust-emissions test variability for a given vehicle in a single test cell has been



MAJOR SOURCES OF EACH LEVEL
OF VARIABILITY

<u>Sources</u>	<u>Cell</u>	<u>Cell-to-Cell</u>	<u>Lab-to-Lab</u>
	Vehicle	Vehicle	Vehicle
	Driver	Driver	Driver
	Ambient Condition	Ambient Condition	Ambient Condition
		Dynamometer	Dynamometer
		CVS	CVS
		Analyzer	Analyzer
		Operator	Calib. Gas
			Operator
			Computer

FIGURE X-1 Factors Affecting Exhaust Emissions Variability of a Given Vehicle at Various Levels.

Source: Reference 10.9

obtained at several laboratories by repeated testing. Typical results are listed in Table X-1.^{10.9} Additional variability has been shown to occur when a vehicle is tested in various cells at a given laboratory.

A fleet of eight vehicles representing four engine families equipped with 1975 single-catalyst emissions systems was tested by Ford Motor Company.^{10.9} This program involved conducting back-to-back CVS-CH tests on the eight vehicles at a single test facility under highly controlled test conditions at each of the mileage intervals prescribed by the Federal Durability Test Procedure. By pooling the standard deviations for mileages, vehicles and families, the analysis separated test-to-test variability from the influences due to mileage, vehicle, family and maintenance. Data from this program are summarized in Table X-2.

Based on these results, it can be expected that variations in exhaust-emissions measurements specified in terms of the standard deviation as a percent of the mean for a 1975-76 vehicle in a given cell or from cell to cell at one laboratory for most engine-control system combinations can be expected to range between 10% to 25%, 15% to 30% and 5% to 15% for HC, CO and NO_x, respectively.^{10.9}

Laboratory-to-laboratory exhaust-emissions test variability has also been examined. The Motor Vehicle Manufacturers Association (MVMA) conducted a lab-to-lab cross-correlation program during 1974 with a specially designed vehicle, REPCA I.^{10.9} This vehicle was specially designed by General Motors to minimize vehicle variability during a modified CVS test, CVS-H, in which the vehicle is fully warmed up prior to initiation of the test. The tests were carried out at General Motors, EPA-Ann Arbor, Chrysler, American Motors, Ford, and International Harvester. Most of these CVS-H tests results for HC, CO and NO_x, except for one laboratory, fell within plus or minus two standard deviations of the mean values. Standard deviations as a percent of the mean for these pollutants were approximately 4.5%, 8.0% and 1.8%, respectively. The CO₂ standard deviation as a percent of the

TABLE X-1

Typical Vehicle-Test Variability for Exhaust Emissions in CVS-CH Tests,
Mean and Standard Deviations are Given as a Percent of Mean

Source	No. of Tests	Emissions in grams/mile ¹					
		$\bar{X}$	$\frac{s}{\bar{X}}$ as %	$\frac{CO}{\bar{X}}$ as %	$\frac{NO_x}{\bar{X}}$ as %	$\frac{CO_2}{\bar{X}}$ as %	$\frac{s}{\bar{X}}$ as %
EPA-1971 Production Vehicle	30	2.46	14.2	16.73	11.3	4.71	6.5
General Motors - Catalyst Equipped Chevrolet Impala	16	0.37	27	4.44	17	2.32	3.4
General Motors - Experimental 1975 Control System Vehicle #1	10	0.27	11.1	3.65	26.3	2.72	8.5
General Motors - Experimental Vehicle #2	11	0.36	16.7	1.97	40.6	14.2	14.1
Honda-CVCC	10	0.29	8.1	2.71	5.4	0.260	4.7
						476.3	2.5

¹Based on CVS-CH test method

$\bar{X}$ is the mean emissions value

$\frac{s}{\bar{X}}$ is the standard deviation as percent of the mean

Source: Reference 10,9

TABLE X-2

Summary of Emissions Test Data for CVS-CH Tests
on the "Riverside" Catalyst-Equipped Fleet

Engine Family	$\overline{\text{HC}}$	$\frac{s}{\overline{\text{HC}}}$	$\overline{\text{CO}}$	$\frac{s}{\overline{\text{CO}}}$	$\overline{\text{NO}_x}$	$\frac{s}{\overline{\text{NO}_x}}$
A	0.748	29	4.50	20	2.55	13
B	0.586	9	5.37	31	2.51	8
C	0.423	17	2.69	24	2.32	9
D	0.679	9	4.21	17	2.90	8
Fleet	0.607	19	4.19	26	2.56	10

Emissions in g/mi

$\overline{x}$ - grand mean of emissions on CVS-CH test, g/mi

$\frac{s}{\overline{x}}$ - standard deviation as percent of the mean

Source: Reference 10,9

mean was approximately 1.8%, and a number of laboratories were reporting CO₂ values that fell outside the mean plus or minus two standard deviations.

Since certification is based on CVS-CH tests, laboratory-to-laboratory correlation tests using this test method have also been reported. The results of a round-robin emissions test carried out on a relatively stable vehicle at various laboratories in the U.S. and at Volkswagen AG in Germany during 1973 have been reported.^{10.10} A statistical test was performed on all measurements obtained and the computations indicated that values reported by some laboratories were suffering from systematic errors as high as 30%. Also, a vehicle equipped with an oxidizing catalyst has been tested several times over the CVS-CH cycle in various cells at Chrysler Corporation and three times in one test cell at EPA - Ann Arbor. The mean values obtained at the two laboratories varied by approximately 25% for HC and CO, were equal for NO_x, and were within 3% for CO₂.^{10.9}

Since systematic errors of 20% to 30% have been reported between various test laboratories, routine mandatory exhaust-emissions correlation test programs between testing laboratories should be established.

An estimate of the statistical variation in exhaust emissions from a group of production vehicles has also been obtained. Data provided by one manufacturer summarizing the results of recent CVS-C quality audit tests of 1974 California production vehicles as a function of engine family are summarized in Table X-3.^{10.9} Inspection of these results indicates that the variability expressed as the standard deviation from the mean for these production vehicles is in the range of 15% to 30%, 20% to 40% and 15% to 25% for HC, CO and NO_x, respectively. Honda has reported the results of CVS-CH tests on thirty-eight production vehicles equipped with a 1.5-liter CVCC stratified-charge engine. The mean values and standard deviation as a percent of the mean for HC, CO and NO_x were reported to be $0.23 \pm 21.8\%$, $2.24 \pm 8.9\%$ and $1.15 \pm 10.4\%$ g/mi, respectively.^{10.9}

TABLE X-3

Summary of General Motors Exhaust Emissions Audit Tests in
California for the Period 01/01/74 through 03/31/74

Make	Engine Family	No. of Tests	HC		CO		NOx	
			$\bar{x}$	$\frac{s}{\bar{x}}$	$\bar{x}$	$\frac{s}{\bar{x}}$	$\bar{x}$	$\frac{s}{\bar{x}}$
Chevrolet	A1	198	1.9	22	21	24	1.6	19
	A2	130	2.0	19	24	27	1.5	19
	A3	234	1.7	32	26	29	1.5	21
	A4	844	1.8	26	29	32	1.4	21
	A5	63	1.9	36	28	32	1.5	23
Pontiac	B1	91	1.9	18	28	23	1.5	22
	B2	3	1.9	8	16	10	1.5	15
	B3	46	2.4	16	23	49	1.5	15
Oldsmobile	C1	75	2.5	19	24	38	1.5	17
	C2	46	1.6	31	21	29	1.4	24
Buick	D1	48	2.4	25	23	40	1.5	21
	D2	49	2.2	25	27	22	1.2	15
	D3	27	2.6	23	23	21	1.7	15
Cadillac	E1	109	2.1	32	24	40	1.8	36

Emissions in g/mi; data based on CVS-C tests

$\bar{x}$ - mean emission value

$\frac{s}{\bar{x}}$ - standard deviation as percent of mean

Source: Reference 10.9

3. Factors Affecting Statistical Variability of Exhaust-Emissions Measurements

An estimate of the sources and relative contributions of various factors to the overall exhaust-emissions variability of a 1975-76 California-type vehicle are shown in Figure X-2.^{10.11} Vehicle variability contributes significantly to the overall CVS-CH test variability. Since a significant fraction of the total mass of both HC and CO is collected in the cold transient phase of the CVS-CH, the cold-start weighting factor in the test method plays an important role on the technological demand placed on control systems. The results of a number of studies designed to evaluate the importance of the cold transient phase on the total mass of HC and CO collected during the CVS-CH test are summarized in Table X-4.^{10.11} In the CVS-CH test method, the total mass of pollutant emissions in the cold transient, hot transient and stabilized portions of the test are weighted by 0.43, 0.57 and 1.0, respectively. Therefore, the contribution of the cold transient phase to the computed vehicular composite emissions in grams per mile is not only dependent on the total mass of pollutant collected, but also on the weighting factors.

It has been suggested that many cars may have a higher percentage of hot starts than is represented by the CVS-CH test method and hence that the cold-weighting of emissions may overemphasize the environmental contribution of CO and HC from cars.^{10.8} Even if true, this effect would tend to be counterbalanced by the significant increases in HC and CO emissions, as compared to those measured in the CVS-CH test, from the large number of cars that are started at temperatures well below 60°F.

Ambient test-cell conditions also contribute significantly to the overall CVS-CH test variability, as illustrated in Figure X-2. The results of tests carried out in an environmental chamber, designed to evaluate the sensitivity of exhaust emissions to barometric pressure and humidity variations, as reported by General Motors, are summarized

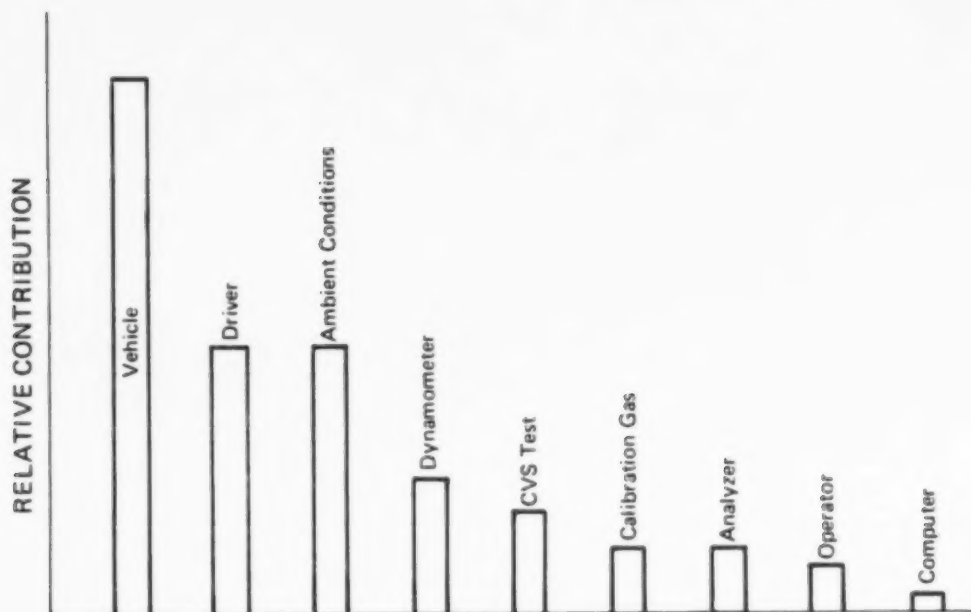


FIGURE X-2 Estimated Sources of Variability and Probable Relative Contribution for Mass Emissions Errors on the CVS-CH Test at 1975 California Levels.

Source: Reference 10.11

TABLE X-4

Contribution of the Cold-Transient Phase of CVS-CH Test
to Total Mass of HC and CO Collected

<u>Vehicle Description</u>	<u>Percentage of Total Mass of Pollutant Collected in Cold-Transient Phase of the Test</u>	
	<u>HC</u>	<u>CO</u>
Average of 30 tests on a 1971 vehicle	52	59
Seven production vehicles ranging from 1967 to 1973	35-51	39-77
Average of 16 tests on a Chevrolet Impala with an oxidizing catalyst	87	94
Average of four 1975 prototype oxidation equipped vehicles	64	73
2.0 liter Honda CVCC vehicle	50-60	30-40

Source: Reference 10.11

in Table X-5.^{10.11} For the sake of comparison, Ford Motor Company data based on multiple regression analysis of three vehicles tested on the CVS-H test cycle are also included in Table X-5.^{10.11} EPA has also reported the results of a series of tests that indicate correlations between CVS-CH exhaust emissions and ambient test-cell temperature, pressure and humidity.^{10.9}

In order to reduce the variability of exhaust-emissions tests, ambient test-cell temperature and humidity should be more carefully controlled than is presently required during the CVS-CH test method. In addition, appropriate correction factors relating ambient pressure and all exhaust emissions should be developed and incorporated in the CVC-CH test method.

Other factors, including the driver, dynamometer, and the combined CVS sampling and gas analytical systems, influence the exhaust-emissions variability. Ford Motor Company^{10.11} has reported that driver variability, within the specified federal tolerances, was found to affect mass emissions by as much as 8%. Dynamometer calibration procedures and roll spacing were also reported to contribute to exhaust-emissions variability. Finally, systematic differences in the combined CVS sampling and gas analytical system of various facilities were reported to range from 2% to 8%.

4. Effect of Ambient Temperature on Exhaust Emissions

A recent study carried out by the Bartlesville Energy Research Center of the U.S. Department of Interior has shown that CVS-CH exhaust emissions can vary significantly over the temperature range (60° to 86°F) allowed in the CVS-CH test method. In addition, emissions increase significantly as ambient temperature is decreased into the ranges commonly encountered in winter in actual use. The temperature dependence of average exhaust emissions for 20 pre-1973 production cars, four prototype 1975 emissions cars with oxidation catalysts, one vehicle equipped with a diesel engine, and one vehicle equipped with a PROCOCO stratified-charge engine are shown in Figure X-3.^{10.12}

TABLE X-5

Effect of Barometric Pressure and Humidity on Exhaust Emissions

<u>Source</u>	<u>Percent Change</u>				<u>Range of Study</u>
	<u>HC</u>	<u>CO</u>	<u>NO_x</u>	<u>CO₂</u>	
One inch Hg increase in barometric pressure					
GM environmental chamber data	-10	-30	+ 5	+2.2	26-30" Hg
Ford data based on ¹ multiple regression analysis of three vehicles	-13.6	-21	+12.5	+7.7	28.7-29.51" Hg
50 grains increase in absolute humidity					
GM environmental chamber data	+10	+25	---	-1.5	30-100 grain/lb dry air

¹Data based on CVS-II tests

Source: Reference 10.11

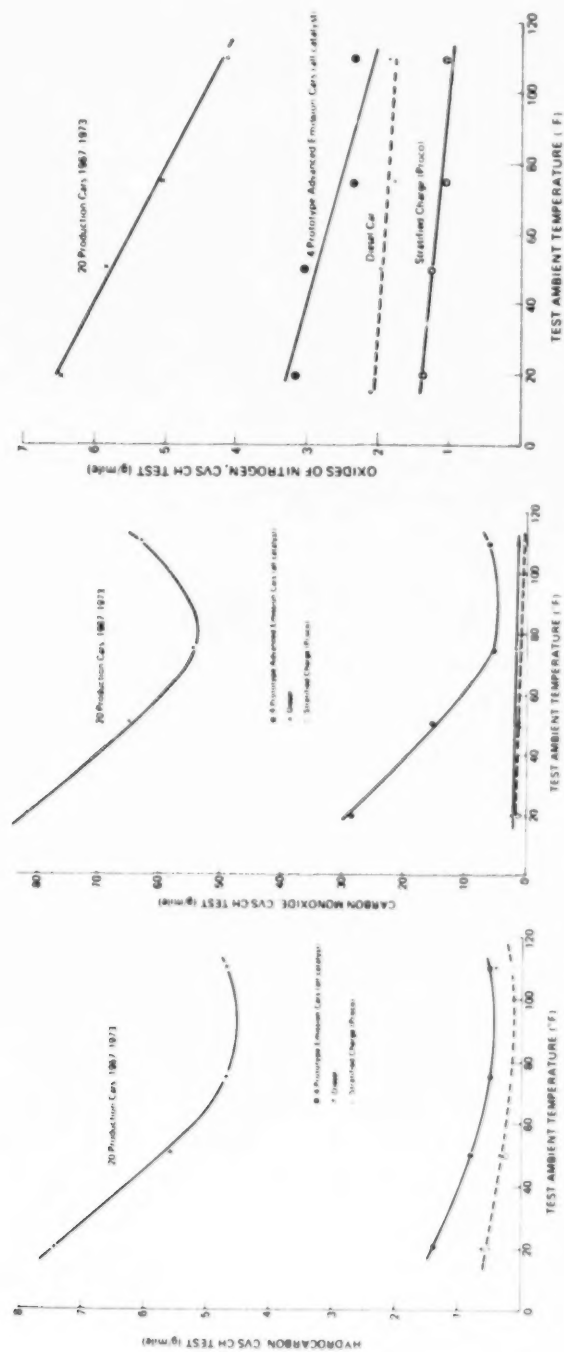


FIGURE X-3 Effect of Ambient Temperature on Exhaust Emissions During the CVS-CH Test.

Source: Reference 10.12

5. Durability Test Methods and Procedures

It has been suggested that statistical variability associated with exhaust-emissions tests may cause errors in the determination of deterioration factors (DF). A statistical simulation technique has been used to estimate potential statistical variations in deterioration factors when only a limited number of durability-data cars are tested for a particular engine-system combination.^{10.13}

Typical results based on statistical simulation for a hypothetical fleet of ten identical vehicles indicating the possible variability in the DF as a function of exhaust-emissions test-to-test variability are listed in Table X-6.^{10.14} Inspection of these results indicates that the mean value of DF for the ten-vehicle fleet is in reasonable agreement with the true value of DF as a function of both the exhaust emissions at 4,000 miles and the test-to-test coefficient of variation. However, the coefficients of variation of the DF's computed for each ten-vehicle fleet are approximately equal to or greater than the corresponding test-to-test coefficient of variation.

These computations indicate that the statistical variability associated with the evaluation of deterioration factors, often obtained from tests on a single durability-data car, may reflect the special circumstances of the test rather than the capability of the underlying technology. An averaging procedure over a larger group of "similar vehicles" would be preferable except for the fact that this can be accomplished only by testing a larger number of cars or by averaging the results from the present number of vehicles over larger subsets. The first approach would be good, if it is not too costly to EPA and the manufacturers, but the latter approach would not be appropriate since it would treat too many vehicles and systems as equal and, hence, attractive technologies would be counterbalanced by less desirable technologies.

TABLE X-6

Monte Carlo Simulation of Possible Variability in Deterioration Factors (DF)
as a Function of Test-to-Test Variability

Emissions at 4,000 miles g/mi	True DF = 1.0						True DF = 2.0					
	COV = 10%		COV = 20%		COV = 30%		COV = 10%		COV = 20%		COV = 30%	
	$\overline{DF}$	$\frac{s}{\bar{x}} \%$	$\overline{DF}$	$\frac{s}{\bar{x}} \%$	$\overline{DF}$	$\frac{s}{\bar{x}} \%$	$\overline{DF}$	$\frac{s}{\bar{x}} \%$	$\overline{DF}$	$\frac{s}{\bar{x}} \%$	$\overline{DF}$	$\frac{s}{\bar{x}} \%$
0.41	0.978	8	1.00	15	1.20	37	2.11	9	2.12	39	2.36	50
1.5	0.931	9	1.05	22	0.966	32	2.02	6	1.99	26	2.19	48
3.1	0.949	12	0.980	19	1.05	24	2.06	11	2.29	29	1.99	22
9.0	1.03	12	0.986	17	1.13	24	2.03	9	1.97	21	2.22	34
15	0.983	11	0.998	19	0.901	23	1.99	11	2.24	16	1.70	20

Fleet size - 10

COV - test-to-test coefficient of variation, %

$\frac{s}{\bar{x}} \%$ - deterioration factor coefficient of variation % from Monte Carlo simulation

$\overline{DF}$ - mean deterioration factor from Monte Carlo simulation

Source: Reference 10.14

D. Evaporative HC Emissions

In addition to HC exhaust emissions, fuel evaporation losses may contribute significantly to the total HC emissions from LDMV's. Until recently, it had been assumed that evaporative HC emissions had been 95% controlled with respect to evaporative emissions equivalent to approximately 3.0 g/mi.^{10.15} This conclusion was based on evaporative-emissions tests employing the Carbon Canister Trap method as presently specified in the Federal Test Procedure.^{10.1}

Evaporative HC emissions measured in two recent EPA surveillance programs,^{10.15, 10.16} employing the SHED test method, indicate that this conclusion is not correct. In fact, evaporative emissions from 1972 model-year vehicles have been shown to be equivalent to approximately 1.9 g/mi in Los Angeles and 2.4 g/mi in Denver.^{10.15} In addition, refueling losses are estimated to be approximately 0.4 g/mi.^{10.15}

These results indicate that reductions in evaporative emissions must be achieved concurrently with reductions in exhaust HC emissions in order to significantly reduce total HC emissions from LDMV's. Also, an accurate test method and procedure for measuring evaporative HC emissions must be developed and implemented as soon as possible. Careful evaluation of this situation may show that the SHED test method is adequate for this purpose.

E. Fuel Economy

1. Vehicle Use Patterns and Driving Cycles

A comprehensive study of LDMV use patterns was carried out by the Bureau of the Census during 1969 and 1970.^{10.17} The annual distribution of trips as a function of trip length, based on the results of this study, is shown in Figure X-4.^{10.18} Most vehicle-miles traveled (VMT) are accumulated during trips over one mile in length. A VMT distribution as a function of trip length, computed from these results, is also shown in Figure X-4. The ratio of rural miles driven to urban

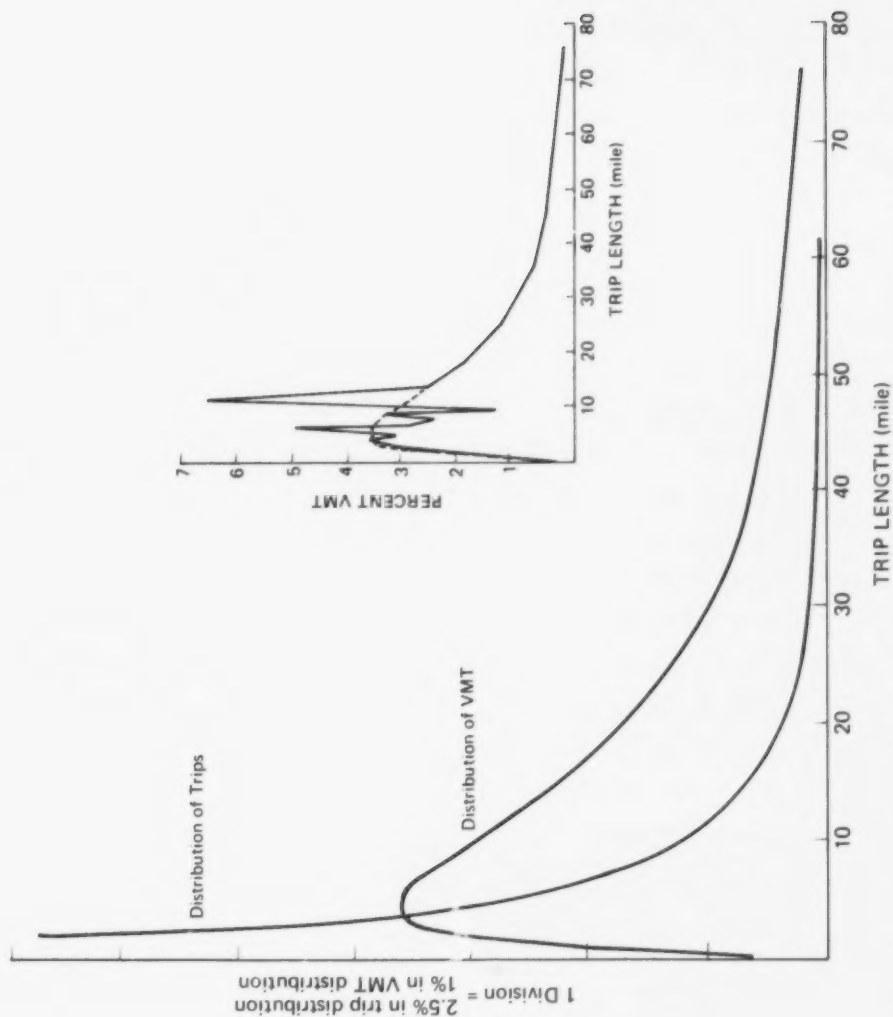


FIGURE X-4 Distribution of LDMV Trips and Vehicle Miles Traveled as a Function of Trip Length.

Source: Reference 10.18

miles driven has varied historically, due to increased urbanization, from 1.1 to approximately 0.82 at the present time.^{10.19}

Various organizations have developed fuel economy driving cycles to test the effects of vehicle design changes and other factors on automotive fuel economy. Fuel economy was determined for a series of steady-state cruise modes at various speeds and for vehicle operation over a number of driving cycles designed to simulate consumer driving patterns in urban, suburban and interstate driving modes. A standardized urban fuel economy driving cycle that could serve as the basis for the accumulation of large amounts of data was not available until EPA suggested that the UDDS could be used for this purpose. Since 1973 they have published significant quantities of fuel economy data, based on this cycle. EPA has also proposed a highway driving cycle for fuel economy measurements.^{10.20} The Society of Automotive Engineers (SAE) has recently recommended the adoption of four fuel economy driving cycles designed to represent driving in an urban environment, a suburban environment and two interstate cycles.^{10.21}

It has been shown that significant vehicular-miles are driven in both urban and nonurban modes, and fuel economy may differ by approximately 50% in these two driving modes.^{10.22} Therefore, in order to obtain a reasonably accurate determination of the fuel economy of a vehicle, two economies, one designed to represent urban driving and one designed to represent highway driving, are needed to provide a rational consumer choice.

Significant fuel economy penalties are incurred when an LDMV is driven on a short trip that is initiated from a cold-start condition. Data indicate (see Figure X-5) that short trips in the range of three to five miles initiated from a cold-start condition can result in fuel economy penalties of as much as 20% to 35% when compared to the fuel economy of a fully warmed-up vehicle for the same trip.^{10.22} In addition, Figure X-4 indicates that more vehicle-miles are driven for trips within 0.5 mile of 4.5 miles than for trips over any other one-mile

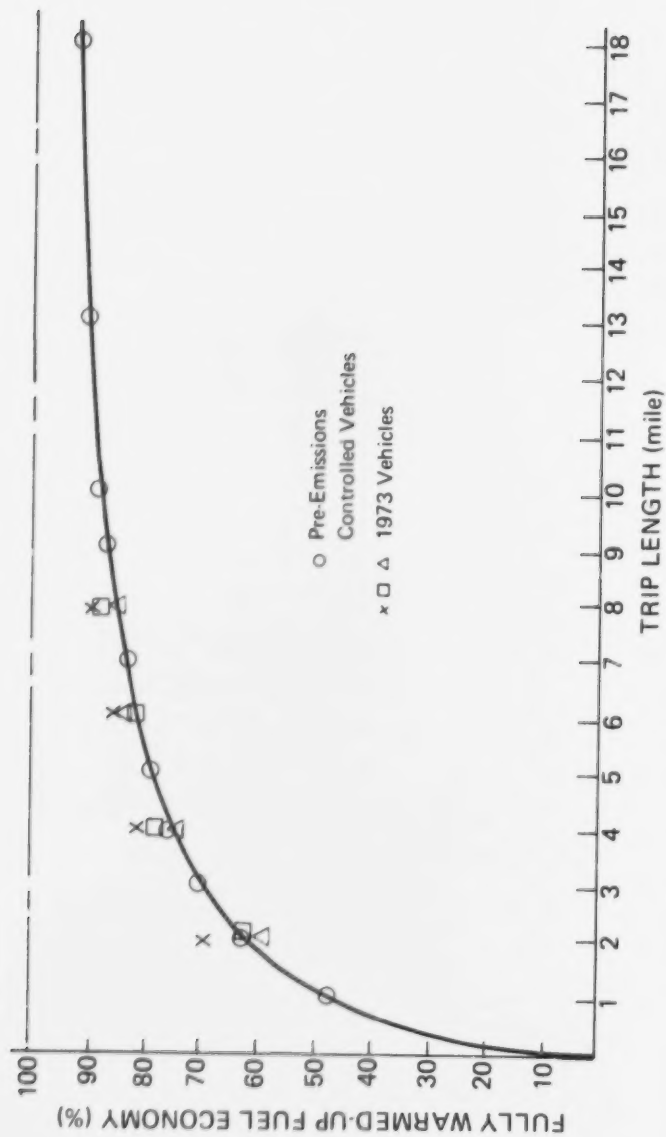


FIGURE X-5 Affect of Trip Length on Cold Start Fuel Economy for an Urban Driving Cycle.

Sources: References 10.22, 10.23

interval. Therefore, in order to obtain economies that are in good agreement with expected real-life urban fuel economies, an urban fuel economy test method and procedure should include a cold-start phase. Since the CVS-CH driving cycle is a reasonable representation of urban driving patterns with a cold-start phase, and since a significant data base of fuel economies has been collected for this cycle, it is concluded that it can be employed as the urban fuel economy driving cycle.

2. Test Methods and Statistical Variability of Measurements

The basic elements in any standardized fuel economy test method and procedure include a representative standard driving cycle or cycles, a method to determine the mass or volume of fuel consumed and the distance traveled during the test, and a procedure for simulating vehicular loads encountered during the course of the driving cycle.

Two methods have been generally used to measure fuel consumption. The first method is based on the direct measurement of mass or volume of fuel consumed during the course of the test. The second method, the Carbon Mass Balance method, is based on the collection and measurement of carbon-containing compounds in the vehicle's exhaust.^{10.24} Both of these test methods for fuel consumption measurements have advantages and disadvantages and are subject to significant errors if careful experimental techniques and procedures are not followed. Alternate satisfactory techniques are available to determine the distance traveled during the test. Fuel economy measurements on the CVS-CH test cycle based on the Carbon Mass Balance method are approximately 3% higher than measurements based on the direct method.^{10.24}

Two procedures have been proposed for simulating vehicular loads encountered during the course of the driving cycle. One method is based on driving the vehicle over a suitable road or test track and the other method is based on driving the cycle on a chassis dynamometer. Both of these procedures have distinct advantages and disadvantages.^{10.24} There is no inherent technical reason for eliminating the use of chassis

dynamometers from fuel economy testing if it can be shown that they adequately simulate the actual inertial, aerodynamic, rolling resistance and accessory loads experienced by a vehicle as it traverses the driving cycle. Unfortunately, the results of definitive studies designed to evaluate the ability of chassis dynamometers to simulate accurately loads under a wide variety of conditions and to evaluate any errors in fuel economy measurements associated with specified errors in dynamometer load simulation have not been reported.^{10.25}

The energy required to drive a vehicle over the CVS-CH cycle has been analyzed, and it has been shown that inertia forces and idle conditions dominate fuel consumption.^{10.26,10.27} Therefore, potential errors in dynamometer simulation of road load encountered during CVS-CH tests should not significantly affect the measured fuel economy. These results and limited data presently available indicate that fuel economy tests incorporating chassis dynamometers, with suitably fine inertia-weight controls, can be successfully employed to determine fuel economies for urban driving cycles where inertia forces and idle conditions, rather than road loads, dominate LDMV fuel consumption.^{10.25}

Fuel economy measurements employing chassis dynamometers for an urban driving cycle (e.g., CVS-H, CVS-C and CVS-CH tests) are considerably more reproducible than exhaust-emissions measurements. In fact, the data indicate that the variability of measured fuel economy in terms of the standard deviation as a percent of the mean in a given cell, from cell to cell at a given laboratory, and from laboratory to laboratory, is in the range of 2% to 9%.^{10.25}

A large number of fuel economy measurements carried out on test tracks have indicated that vehicle-to-vehicle variation in fuel economy for identical vehicles is of the order of 3.5% of the mean fuel economy. In addition, a study designed to determine the variability of results from both test track and chassis dynamometer fuel economy tests concluded that with a single vehicle the true population mean can be established within approximately 7% for the Ford city-suburban driving cycle on a

test track and approximately 11% for the urban CVS-C test cycle on a chassis dynamometer with 90% confidence. The determination of fuel economy for a fleet of "identical" cars to within 3% with 90% confidence was estimated to require testing of five vehicles for the test-track cycle compared to 14 vehicles for the laboratory chassis dynamometer cycle.^{10.25}

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APPENDIX A

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APPENDIX C

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Air Quality Bureau Environment Agency Chiyoda-Ku, Japan	Bureau of Air Pollution Control for New York City Brooklyn, NY
American Motors Corporation Detroit, MI	Bureau of Auto Repair State of California Sacramento, CA
American Oil Company Whiting, IN	Bureau of Mines Bartlesville Energy Research Center Bartlesville, OK (Interview in Denver, CO)
Atlantic Richfield Company Chicago, IL	California Air Resources Board El Monte, CA
Audi Ingolstadt, West Germany	Jay Carter Enterprises Burkburnett, TX
Autotronics Controls El Paso, TX	Caterpillar Tractor Company Davenport, IA
Bell Laboratories Murray Hill, NJ	Caterpillar Tractor Company Peoria, IL
Bendix Detroit, MI	Caterpillar Tractor Company York, PA
AB Svensk Bilprovning Vallingby, Sweden	C.A.V. London, England
Robert Bosch GMBH Postfach, West Germany	Chrysler Corporation Detroit, MI
British Leyland, Ltd. Coventry, England	

Cincinnati Milacron
Cincinnati, OH

Clyde Engineering Service
(Meeting in Evanston, IL)

Corning Glass Works
Corning, NY

Cross Manufacturing Company
Detroit, MI

Curtiss-Wright Corporation
Wood-Ridge, NJ

Daihatsu Kogyo Company, Ltd.
Osaka, Japan

Daimler-Benz AG
Stuttgart, West Germany

Datsun
Tokyo, Japan

Daug (Deutsch Automobilegesellschaft)
Frankfurt, West Germany

Department of Environment
London, England

Department of Transportation
Transportation Systems Center
Cambridge, MA

Dresser Industries
Santa Ana, CA

E. I. duPont de Nemours and Company,
Incorporated
Wilmington, DE

Engelhard Industries
Murray Hill, NJ

Environmental Protection Agency
Emission Control Technology Division
and
Surveillance Branch
Ann Arbor, MI

Environment Canada
Hull, Quebec

ESB Company
Yardley, PA

Ethyl Corporation
Ferndale, MI

Excello Corporation
Detroit, MI

Exxon Research and Engineering
Linden, NJ

Fiat, S.p.A./Ferrari
(Meeting in Washington, DC)

Ford Motor Company
Dearborn, MI

Ford Motor Company
Rawsonville, MI

General Motors Corporation
Warren, MI

General Motors Corporation
Tonawanda, NY

General Motors Corporation
Milwaukee, WI

Gilman Engineering
Janesville, WI

Gleason Manufacturing Company
Rochester, NY

Gould, Incorporated
Cleveland, OH

Gulf Research and Development
Pittsburgh, PA

Holley Carburetor
Detroit, MI

Honda Motor Company, Ltd.
Tokyo, Japan

Honda Research and Development
Company, Ltd.
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IGT
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Control
Trenton, NJ

New York City Air Resources
Board
New York, NY

New York City Bureau of Air
Pollution
New York, NY

New York City Taxi Commission
New York, NY

New York State Bureau of Air
Quality
Albany, NY

Nissan Motor Company, Ltd.
Tokyo, Japan

Olsen Laboratories, Incorporated
Anaheim, CA

Adam Opel AG
(Meeting in Washington, DC)

Oxy-Catalyst
West Chester, PA

Perkins Engine Company
Peterborough, England

Peugeot, Incorporated
(Meeting in Washington, DC)

Philco-Ford
Newport Beach, CA

Phillips Research Laboratory
Eindhoven, The Netherlands

Pollution Control Industries,
Incorporated
Torrance, CA

Popular Science Office
New York, NY

Questor Corporation
Toledo, OH

Regie Nationale des Usines Renault
(Meeting in Washington, DC)

Ricardo and Company Engineers, Ltd.
Sussex, England

Saab-Scania Aktiebolag
Trollhattan, Sweden

Scientific Energy Systems
Watertown, MA

Shell Research, Ltd.
Thornton, England

Society of Automotive Engineers
Fuel Economy Measurement Procedures
Task Force
Romulus, MI

Solar
San Diego, CA

State of New York Bureau of Air
Pollution Control
Albany, NY

Steam Power Systems
San Diego, CA

TACOM
Detroit, MI

Taxi Inspection Lane New York City
Long Island, NY

Texaco, Incorporated
Beacon, NY

Thermo-Electron Corporation
Waltham, MA

Toyo Kogyo Company, Ltd.
Hiroshima, Japan

Toyota Motor Company, Ltd.
Aichi, Japan

Union Oil Company
Brea, CA

United Stirling
Malmo, Sweden

Universal Oil Products
Des Plaines, IL

Vehicle Inspection System
Chicago, IL

Vereinigung Deutscher
Automobilhersteller
Frankfurt, West Germany
(Interview in Geneva, Switzerland)

Volkswagen of America, Inc.
Englewood Cliffs, NJ
(Meeting in Washington, DC)

Volkswagenwerk AG
Wolfsburg, West Germany

AB Volvo
(Meeting in Washington, DC)

Williams Research
Detroit, MI

Yamaha
(Meeting in Tokyo, Japan)

Yanmar Diesel
Osaka, Japan

The Zwick Company
Santa Ana, CA

GLOSSARY

A/F.....	air/fuel
AMA.....	Automobile Manufacturers Association
AMC.....	American Motors Corporation
ASIA.....	Automotive Service Industry Association
AT.....	automatic transmission
CCS.....	direct-fuel-injected, stratified-charge engine such as the Ford PROCO or Texaco TCCS
CID.....	cubic inch displacement
CMVE.....	Committee on Motor Vehicle Emissions
CNG.....	compressed natural gas
CR.....	compression (or expansion) ratio
CVCC.....	prechamber, dual-carburetor stratified-charge engine such as the Honda Motor Company Compound Vortex-Controlled Combustion Engine
CVS.....	constant volume sample emissions test procedure
CVS-CH.....	constant volume sample--cold and hot start emissions test procedure
Cyl.....	cylinder
DF.....	deterioration factor
Dual Cat....	a reducing catalyst followed by an oxidizing catalyst
EFI.....	electronic fuel injection
EGR.....	exhaust gas recirculation
EPA.....	U.S. Environmental Protection Agency
FI.....	fuel injection
FTP.....	Federal Test Procedure
GM.....	General Motors Corporation
g/mi.....	grams/mile of emissions
GT.....	gas turbine
HC.....	various hydrocarbon compounds
HCAT.....	oxidizing catalyst system for removal of HC and CO
ICE.....	internal combustion engine
IFC.....	integrated fuel control (carburetor)
JPL.....	Jet Propulsion Laboratory, California Institute of Technology

LBS..... lean-burn engine system
 LDMV..... light-duty motor vehicle
 LPG..... liquefied petroleum gas
 M/C..... Manufacturing and Costs Panel of CMVE
 Modif..... standard internal-combustion engine modified with emissions
 controls such as spark retard and air pump
 MON..... motor octane number
 mpg..... miles per gallon fuel economy
 MT..... manual transmission
 MVMA..... Motor Vehicles Manufacturers Association
 NIASE..... National Institute for Automotive Service Excellence
 NO_x..... various nitrogen oxide compounds
 P..... production
 PCV..... positive crankcase ventilation
 P..... pre-production
 PROCO..... Ford--Programmed Combustion Process (direct-fuel-injected,
 spark-ignited, open-chamber, stratified-charge engine)
 R..... research
 RE..... rotary engine
 RON..... research octane number
 SAE..... Society of Automotive Engineers
 SHED..... sealed housing for evaporative (emissions) determinations
 std. dev.... standard deviation
 TCCS..... Texaco controlled combustion system (direct-fuel-injected,
 spark-ignited, open-chamber, stratified-charge engine)
 3-way cat... combined oxidizing and reducing catalyst
 UDDS..... urban dynamometer driving cycle
 VMT..... vehicle miles traveled